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Structural design and analysis of Marinaressa Coral Tree

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Abstract
This paper describes the structural design and analysis of a lightweight concrete structure—the Marinaressa Coral Tree—presented at the Venice Architecture Biennale 2023. The prototype was fabricated using 3D-printed water-soluble sand formwork, which allowed the realization of complex filigree geometries while avoiding production waste by recycling the formwork material directly within the formwork manufacturing process. Production technology prompted us to rethink structural design possibilities and create a design solution that allowed for a 60 % reduction in material consumption compared to a solid structure of the same load-bearing capacity. This paper presents the detailed process of its structural design and analysis, including topological optimization of the global design domain at the macroscale and components at the mesoscale, followed by the structural analysis and validation of the load-bearing capacity of the design solution, as well as its global and local behavior under various loading conditions. The study showed that the spatial concrete lattice structure underlying this approach combines strength, dynamic stability, and lightness and can be helpful in the design of concrete structures with minimal environmental footprint.

Keywords: lightweight concrete structure, zero-waste production, water-soluble formwork, topology optimization, conformal lattice, 3D printing, structural design.

1. Introduction
The Marinaressa Coral Tree is a filigree lightweight fiber-reinforced concrete structure measuring 2.7 m x 2.7 m x 3.2 m (h), produced using recyclable sand formwork (Figure 1). The structure was designed and built for the 18th Venice Architecture Biennale and was exhibited from May to November 2023 in the Venetian public garden of Marinaressa. The project's main goal was to show a holistic approach to realizing lightweight concrete structures with a minimal environmental footprint. Demonstrating this approach, the structure's design was based on three mutually reinforcing principles: *minimality*, *circularity*, and *regenerability*. The structure's weight was reduced by 60 % using structural optimization techniques while maintaining the main stiffness parameters. Its realization was made possible using a water-soluble, recyclable sand formwork, resulting in zero-waste production. Finally, by reducing the cross-sectional area of the components and increasing the surface area of the structure, it was possible to maximize the ability of the filigree concrete lattice to absorb carbon dioxide from the atmosphere, allowing it to offset its embodied emissions over the service life.

1.1 Research context
The Marinaressa Coral Tree is the construction-scale demonstrator built within the research project devoted to investigating sustainable production methods for lightweight concrete structures. The project is fully anchored into the research strategy of the ILEK (Institute for Lightweight Structures and Conceptual Design) [1], following an integral approach to reducing resource consumption, emissions,

Figure 1: View of Marinaressa Coral Tree in Marinaressa garden of Venice.

and waste. The research is embedded into the broader context of activities to achieve carbon neutrality in concrete construction by 2050, which, based on multiple analyses, can only be reached via cumulative effort at all scales, from cement to building systems and throughout the value chain [2]. In this context, applying lightweight construction principles to the design of concrete structures is seen as an inevitable prerequisite for sustainable change in the industry. The ILEK approach to lightweight concrete systems has its roots in the concept of functional gradation formulated by Prof. Werner Sobek [3]. Functional gradation enables the material to be minimized by purposefully distributing it according to the stress state within the structure under given loads. Typically, the material distribution in the form of a gradation layout is modeled using structural optimization methods.

Yet, the materialization of the graded system is determined mainly by the chosen production technology. Thus, one of the main problems in realizing such lightweight concrete structures is the choice of production methods that combine feasibility with environmental sustainability. One of the key aspects to be addressed is formworks, which are still associated with significant time and labor expenses and massive waste production when it comes to complex geometries.

1.2. Zero-waste fabrication with water-soluble 3D printed sand formworks

To address the above-described problem, the technology for the zero-waste production of geometrically complex concrete structures was developed in the framework of this research. The complex formwork shapes for concrete casting are produced in powder-bed-based 3D printing process from a specially designed mixture of sand and an organic water-soluble binder [4]. The binder (dextrin), supplied in powder form and homogeneously mixed with sand, is activated when wet with water and hardens when it evaporates so that the formwork can withstand the hydrostatic pressure of the concrete during casting. Wetting the hardened mixture causes the bonds to dissolve and the formwork to decompose. Since the hardening of formwork is based solely on physical processes, i.e., without chemical reactions, the molds are reversibly stable and easily recyclable. A custom-made 3D printer was designed and built with a 700 x 1000 x 400 (h) mm^3 powder bed to produce construction-size components. Sand formworks for Marinaressa Coral Tree (in total 56 segments) were printed on this machine to cast all concrete modules (Figure 2). After the concrete was cured, the components were demolded with room temperature water, and the formwork material was collected, recycled, and reused within the same production cycle.

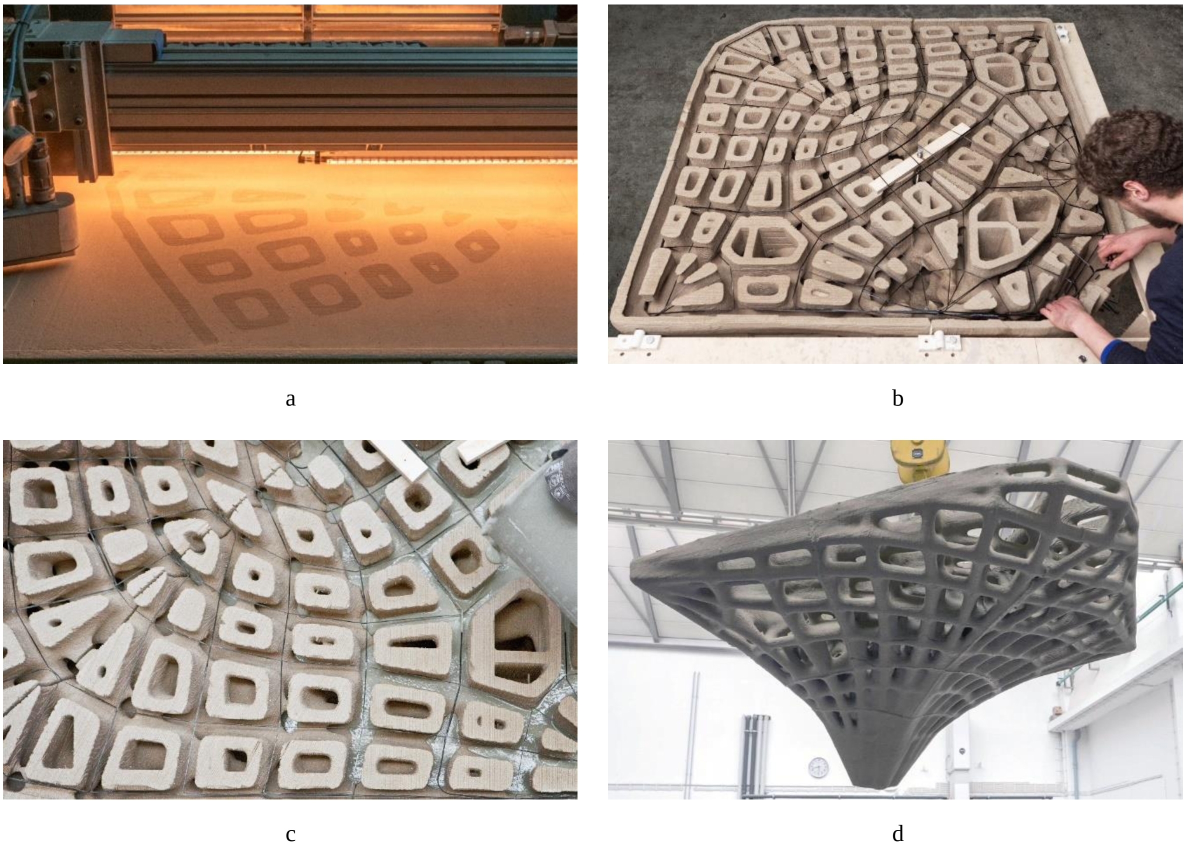

Figure 2: Fabrication of Marinaressa Coral Tree with 3D-printed water-soluble sand formworks: 3D printing of formwork segment (a), assembly of formwork for casting (b), casting of self-compacting concrete (c), and view of one concrete module (d).

An essential aspect of this research was investigating the inverse effect of this production method on the design potential of lightweight concrete structures. Since the formwork is inherently temporary, it is possible to create reinforced concrete elements of almost unlimited complexity without the geometric constraints usually imposed by demolding with classical methods, such as negative angles, undercuts, and bottlenecks. This fact has prompted us to rethink the typical design approach for functionally graded concrete structures and to investigate the application of new structural morphologies, such as spatial lattices and multiscale optimized systems, which are known from theoretical studies but weren't yet practically realizable in reinforced concrete due to production constraints.

2. Structural Design of Marinaressa Coral Tree

It is generally known that statically efficient structural behavior can be achieved by designing the structure in such a way as to maximize load transfer through axial forces and minimize bending moments. Many shape and topology optimization techniques are available today to achieve this goal. Particular interest, mainly due to advances in digital fabrication and additive manufacturing, have recently attracted multi-scale and lattice structures as they promise to achieve superior performance while being intrinsically lightweight, robust, and multifunctional [5]. The optimization of multi-scale structures is based on the homogenization-based topology optimization approach. Here, the effective representation of macrostructural behavior within the design domain is presented by the orthotropic microstructures locally modulated and oriented along principal stress directions, providing highly efficient designs [6]. This approach set the basis for the design of this demonstrator, leading to the generation of a conformal lattice structure. Its layout follows the principal stress trajectories: the compressive forces are transferred via concrete struts and tensile forces via the tailor-placed carbon fiber reinforcement. In the following section, the design workflow will be presented, including topology optimization of the global design domain, its segmentation into individual components, the optimization of components at the mesoscale, and the modeling of the conformal lattice structure.

2.1. Optimization of the global design domain

As a general shape for the prototype, a section of a classical load-bearing structural system of a multistory building consisting of a flat slab resting on columns (Figure 3a) was chosen; in particular, its cutout in the slab area above the columns near the zone of zero moments (Figure 3b). The structure in this area acts as a cantilever slab with the highest tensile stresses in the upper slab zone and compressive stresses in the bottom slab zone, transferring the load through the capital to the supports. Generally, the stress field in this region can be expected to be very heterogeneous, opening many possibilities for optimizing material consumption (both concrete and reinforcement).

The global design domain was optimized regarding material distribution in the first design step to provide the main guidelines for the structure's segmentation. For this, the simplified 2D topology optimization was conducted using a homogenization-based approach as the minimal compliance problem with the target volume fraction of 0.5 at the design loads of dead weight and a distributed load of 5 kN/m² (Figure 3c). The process included three steps: 1) the calculation of the homogenized mechanical properties (stress tensor) of a chosen microstructure (square cell with variable wall thickness), 2) the optimization of the homogenized problem, and 3) the projection of the modulated and oriented microstructure at the desired length scale [7].

Figure 3c depicts the resulting multiscale structure with material distribution under the given loads represented by the modulated and oriented lattice at the mesoscale. The high-density areas are present in the upper (tensile) and lower (compressive) slab zones, lower capital areas, and perimetral zones of the column. Instead, the low-density regions are located in the center of the capital and the column. The optimization performed provided guidelines for segmenting the structure into individual modules and locating all the necessary interfaces between them.

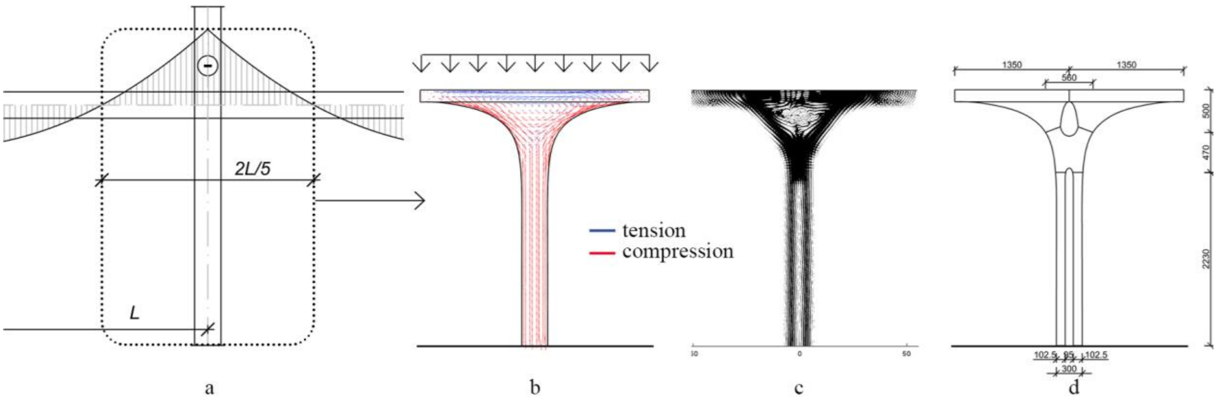

Figure 3: Overview of the process of structural design of the prototype: (a) initial design domain, (b) topology optimization with homogenization method, (c) refined design domain and modularization concept, (d) structural analysis of the modularized structure.

2.2. Modularization of the structure

The exhibition object's temporary nature, assembly, and transport constraints imposed specific requirements on individual components' maximal dimensions and weight. Therefore, based on the results from the preliminary optimization procedure, the global design domain was divided into nine separate components, including four upper slab modules of 1.35 x 1.35 x 0.51 (h) m, the capital module of 0.6 x 0.6 x 0.6 (h) m, and four column modules of 0.1 x 0.1 x 2.1 (h) m (Figure 3d). To optimize the load transfer from module to module and to cope with tolerances, the number of connections has been reduced to the necessary minimum, also addressing issues of structural stability. The upper modules have punctual connections between each other in the upper zone to transfer the tensile forces and to the capital to transfer compressive and tensile forces. The capital has, in turn, the connections to the columns to transfer the compressive and tensile forces down to the foundation.

2.3. Mesoscale optimization of individual components

In the next step, a mesoscale optimization of the individual components was carried out. It is based on a homogenization-based approach, which was extended to the 3D space from the previously described 2D problem. Compared to the 2D case, where the orientation of the conformal lattice is accomplished using a single angle of the principal stress vector, the conformal 3D lattice is constructed through the intersections of a triply orthogonal system of surfaces constructed along pairs of principal stress vectors [8].

Figure 4 shows the workflow of modeling the conformal 3D lattice structure for an upper slab module under the design loads (self-weight + distributed load of 5 kN/m² to the upper surface). The modeling starts with the export of three principal stress vectors (σ1, σ2, σ3), which serve as input data for constructing three groups of surfaces (Figure 4a). The surfaces in each group are reconstructed incrementally using a tracing algorithm along the orientations of the planes formed by the respective vector pairs (σ1+σ2, σ2+σ3, σ3+σ1) (Figure 4b). The distance between the surfaces is chosen based on the desired scale of the resulting structure and the fabricability constraints. Theoretically, the smaller the mesostructure's scale, the higher the stiffness of the resulting lattice will be [6]. The average spacing between the surfaces of 150 mm at the peripheral area of the component was chosen, considering the convergence of the structure around the support region. Further, each surface group intersects with two others (Figure 4c), resulting in the three networks of curves following one of three principal stress vectors. Finally, the intersection of the three groups of curves results in the desired conformal lattice with cubic cells locally oriented along the three principal stress trajectories at every point of the stress field (Figure 4d).

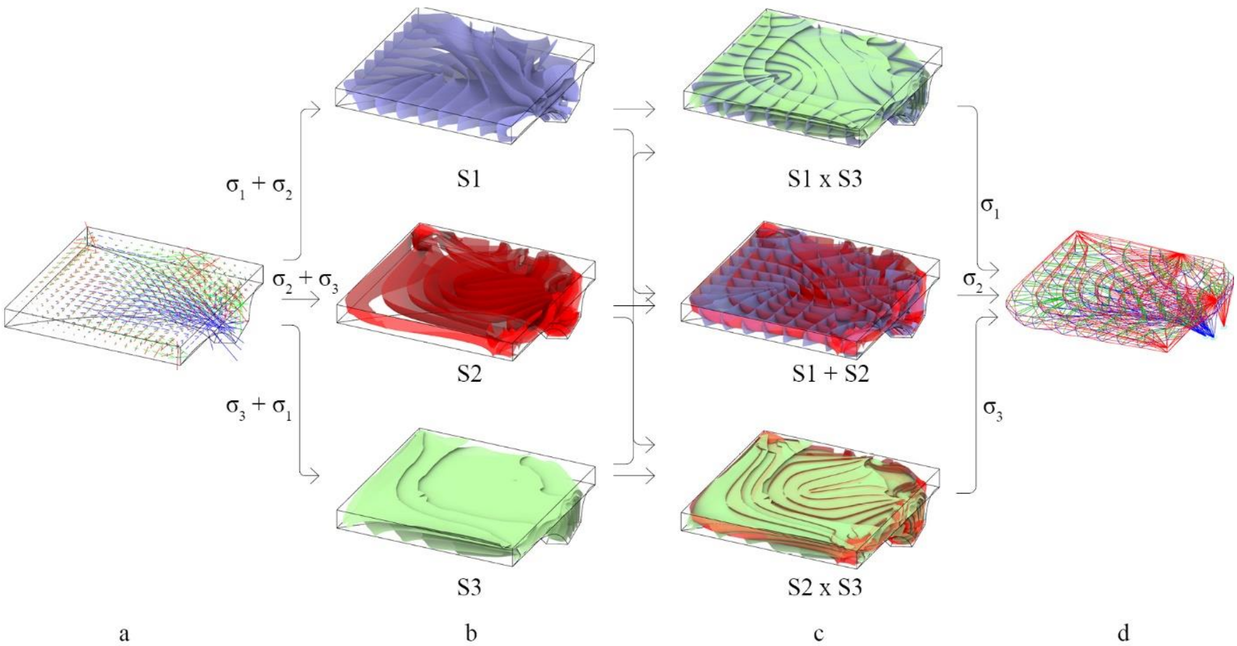

Figure 4: Meso-scale optimization of individual components: extraction of three principal stress vectors from the stress field (a), reconstruction of the three groups of triply orthogonal surfaces along the pairs of principal stress vectors (b), intersection of the groups of surfaces to achieve networks of curves (c), conformal 3D lattice compiled from three groups of curves (d).

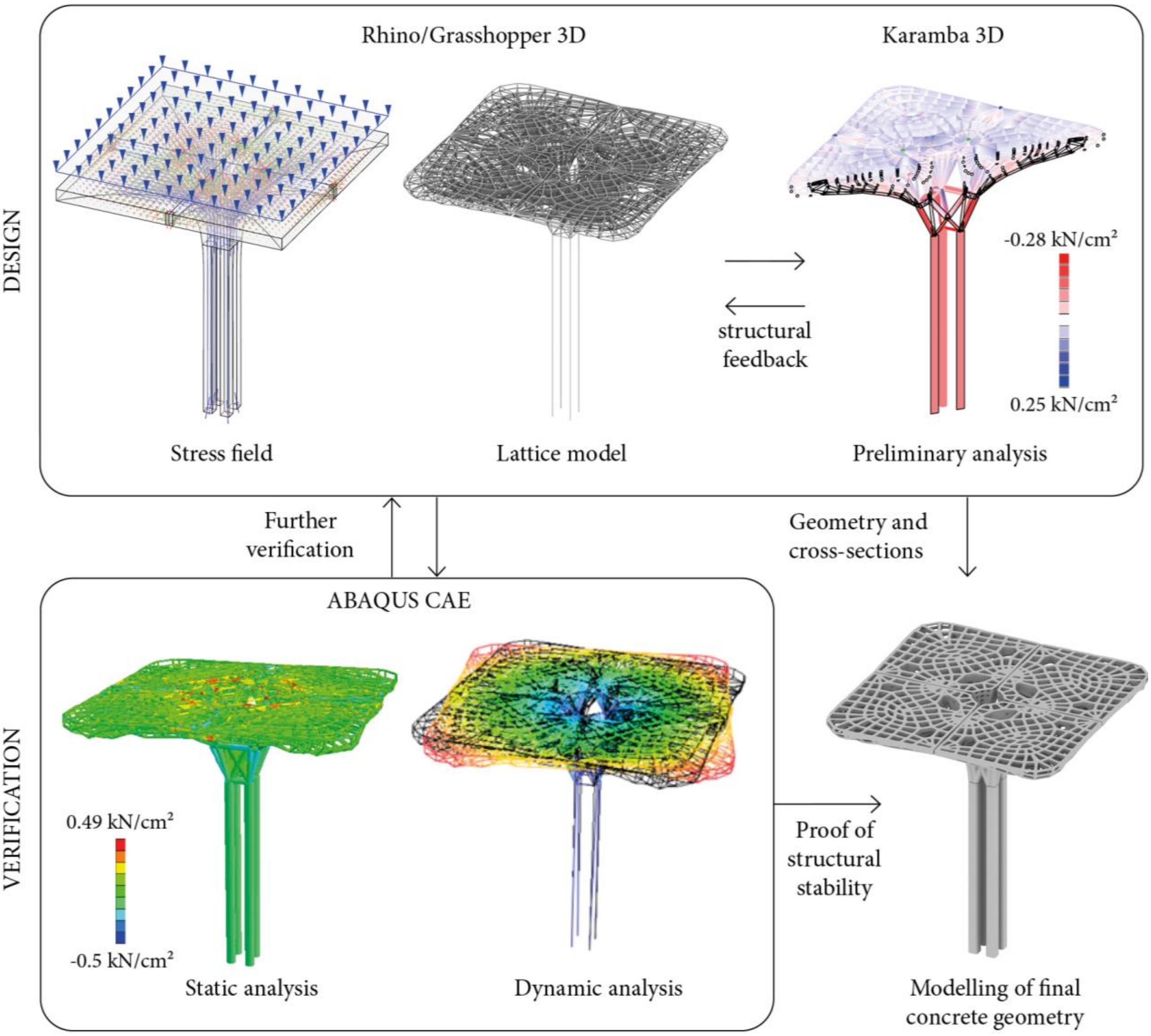

Figure 5: Workflow of structural design and analysis of Marinaressa Coral Tree.

3. Structural analysis and validation

In the next step, a structural analysis of the modeled lattice was performed to evaluate the actual stresses in the struts and assign the required cross-sections for compression and tension members. For the calculation, the lattice model was assembled for the entire structure, including all nine modules: the four upper slab modules, the capital, and the four columns. The structural analysis was performed iteratively (Figure 5) with the preliminary analysis in Karamba 3D (structural plugin in Rhinoceros/Grasshopper 3D environment), followed by a more refined analysis in Abaqus CAE. Initial analysis was carried out to verify the topological optimization results, analyze the overall behavior of the lattice structure, and assign preliminary cross-sections to test the manufacturability of the structural design solution. After the final solution was developed, a detailed analysis was carried out to evaluate the static and dynamic performance of the structure under various design loads, as well as the behavior of individual structural elements, connectors, and reinforcement.

3.1. Preliminary structural analysis in Karamba 3D

The lattice model for the entire structure was analyzed in Karamba 3D under various loading conditions, including self-weight + a) distributed load of 5 kN/m² on the entire top surface of the structure, b) distributed load of 5 kN/m² on ¼ of the structure and c) wind load acting on the one side of the structure with the safety coefficient of 1.35 and a utilization degree of 0.6. Concrete C30/37 and steel 235 (for connectors) were used as the materials for the calculation. The analysis was performed in the linear elastic domain using the second-order theory of small deflections and a cross-section optimization module. Figure 5 presents the diagram of the axial stresses in the structure under the self-weight and distributed load of 5 kN/m² applied to the top of the slab surface. As expected, the structure acts as a cantilever with a clear distribution of tensile and compressive stresses in the struts. Axial tensile stresses, reaching maximum values of 0.251 kN/cm², are located in the lattice struts of the upper slab area. The compressive stresses are present in the bottom area of the slab segments, capital, and columns, reaching the maximal values of -0.281 kN/cm². The cross-sections of the struts (taken as solid circular cross-sections) vary in the range from 3 cm in diameter in the upper lattice area to 9 cm in diameter in the columns. The tensile forces in the connections between the upper segments vary from 5.9 kN in the central area to 2.7 kN in the periphery.

3.2. Detailed structural analysis in Abaqus CAE

A more refined structural analysis was carried out using the FE program Abaqus CAE. The analysis was used to verify the preliminary analysis carried out in Karamba 3D and as a data basis for the structural documentation for the Italian authorities. The underlying geometry was created in Abaqus using a Python script automatically generated in the Grasshopper 3D environment. The model was assembled from nine elements: four slab elements, the capital, and four individual columns. Linear material properties of a concrete C50/60 were used throughout the model. The slab elements consisted of circular concrete rods with a diameter of 20 mm. The capital was idealized for the analysis through concrete rods with a diameter of 60 mm. Continuum effects from densification and overlapping of the rods were neglected in the slab and the capital. The columns were modeled as concrete bars with a diameter of 100 mm. The connections between the slab elements are modeled as hinged. All other connections, namely the connections between slab and capital, capital and columns, and between columns and foundation, were modeled as rigid. Foundation is realized through two 2.4 m long diagonal steel beams, intersecting each other under the column and resting on concrete plates at their ends. This secures the structure against overturning and provides allowable stress distribution to the soil below.

Five load cases were analyzed in the static analysis: LC 01 comprised the self-weight; LC 02 additionally had a distributed load on the entire top surface (LC 02.01) or a quarter of the top surface (LC 02.02). In LC 03, self-weight and wind were analyzed. LC 04 concerned the somewhat far-fetched case of an over-motivated and overweight exhibition guest attempting to climb the pavilion.

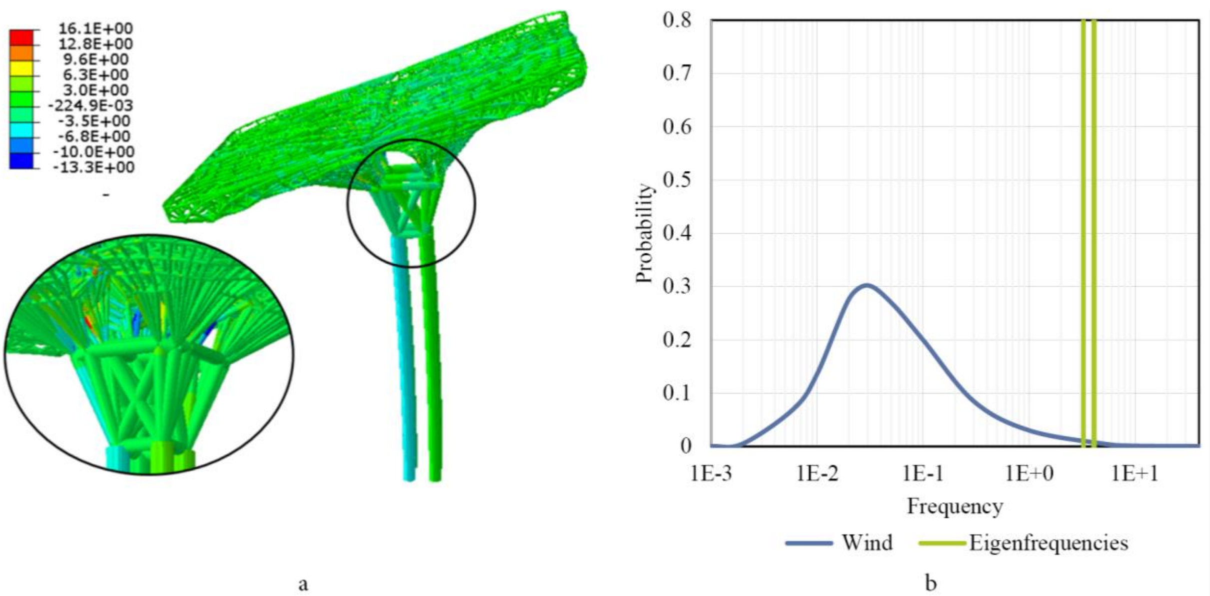

Figure 6: Structural analysis in Abaqus CAE: normal stresses (given in MPa) in rod-elements for the leading load case LC 03 (right, self-weight and wind) (a), and comparison of first three eigenfrequencies with usual frequencies of wind (b).

The first three natural frequencies and their corresponding natural shapes of the structure were also analyzed and evaluated against expected wind frequencies in a dynamic analysis. The loads and design limits were chosen conservatively: all limits, including the deformations, were assessed in the ultimate limit state. The wind load selected of 1 kN/m^2 was significantly higher than the magnitude demanded by Eurocode 1. Moreover, the wind reduction effects of the perforated geometry of the slab elements were neglected. The distributed vertical load was set to 3 kN/m^2 as a more realistic scenario.

In summary, all design criteria with conservative assumptions and limits were well within compliance boundaries for the static analysis. The force fields in the structure under the self-weight load case on which the design is based were similar to those shown in Karamba 3D and the initial stress field. Tensile stresses occurred as expected, but only significantly in areas that would later be equipped with sufficient reinforcement. The load cases LC 02.2 (self-weight and quarter surface load) and LC 03 (self-weight and wind) were decisive here. LC 03 (Figure 6a) was decisive for horizontal and vertical deflection but with a low utilization of the conservative limit values. LC 04 was not decisive in any way. The first three natural frequencies were a rotational frequency at 3.26 Hz and two translational frequencies at 4.09 Hz and 4.12 Hz. As shown in Figure 6b, these frequencies lie reasonably outside the spectrum of expected wind frequencies. Thus, further analysis of the dynamic load-bearing behavior was not considered necessary.

3.3. Structural detailing

Based on the optimized cross-sections of the preliminary analysis and the verified ones of the refined analysis, the cross-sections were assigned for all structural elements, including the upper lattice with a minimum cross-section of 30 mm, the capital with a cross-section of 60 mm and the columns with a cross-section of 100 mm. A combination of several parameters influenced the cross-sectional values: 1) the required load-bearing capacity of the structural members under the decisive load case, 2) the required concrete coverage of fiber reinforcement of at least 15 mm, and 3) the provision of complete filling of the formwork with self-leveling concrete. Using the assigned cross-sectional values, the final concrete structure was modeled in Grasshopper 3D using a volumetric modeling approach and exported as a watertight mesh, which served as the basis for modeling the formwork segments for 3D printing (Figure 7b and c). The weight of the final structure amounted to 1.7 tons, which is 60 % lighter than the weight of a solid structure of the same overall dimensions.

Following the analysis, carbon fiber reinforcement was placed in the tensioned lattice elements located in the upper slab zone, capital, and columns (Figure 7b). The reinforcement material used was polymer-coated Tenax carbon fiber yarns with a cross-section of 64,000 fibers and a tensile strength of 10 kN. As expected, the columns were the only structural members that exhibited significant bending action.

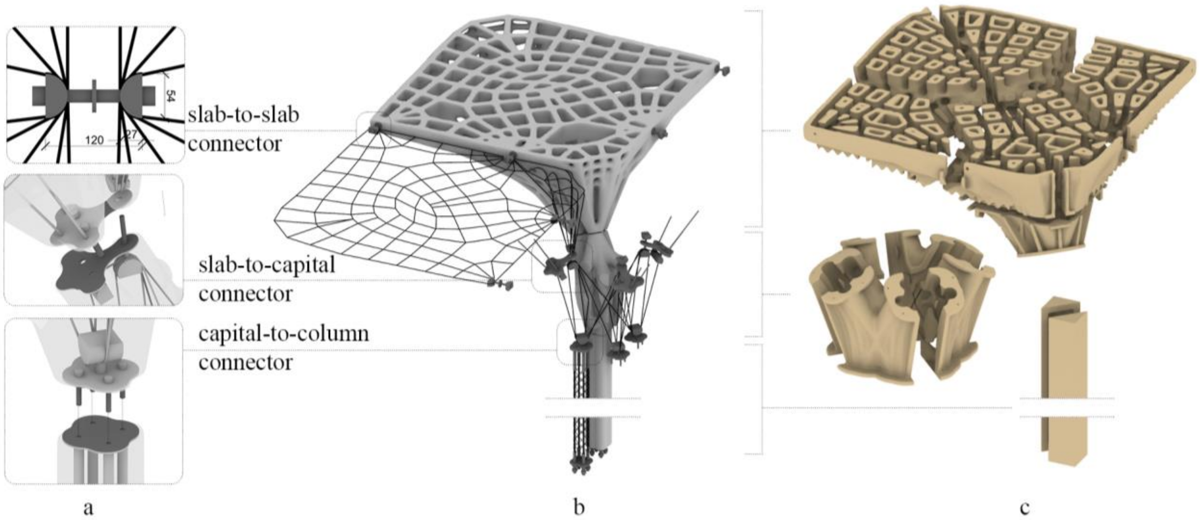

Figure 7: Structural detailing, including design of connections (a), assignment of cross-sections and design of reinforcement (a), and modeling of formworks (c).

They were reinforced with circumferentially distributed bar reinforcement and polymer-coated carbon fiber mesh. The same tensile strength was assumed for the carbon rebar reinforcement as for a steel rebar of a similar dimension. Under this assumption, a bending capacity of 1.56 kNm was assumed.

To provide the effective load transfer from module to module, the steel connectors inserted into concrete were designed according to the required loading profile (Figure 7a). The slab-to-slab connection was designed as a hinged point connection to transfer tensile forces. It consisted of two semicircular embedded steel parts for anchoring the reinforcement in the respective segments and a bolt to connect them. The radius of the built-in parts was dimensioned 32 mm. This would ensure that the shear force within the carbon fibers would be sufficiently small so that the normal force capacity of the fibers could be utilized almost fully. The slab-to-capital connection is made via metal plates in contact. Compressive forces and, to a limited extent, shear forces were transmitted directly. For larger tensile forces, the two plates were connected to each other via a screw. The analysis results indicated a maximum tensile force of 5.1 kN, which could be transmitted with a high degree of safety using the intended M10 screw. The capital-to-column connection is rigid. The moment capacity is achieved by a group of threaded bars anchored from the capital to the corresponding sleeves in the column. The column's reinforcement bars were anchored to the sleeves cut from the opposite side. The bars are inserted during assembly and glued in place after exact positioning. The connection of the column to the foundation is analogous to the connection to the capital. The threaded bars stick from the column and are screwed to the metal foundation construction while assembly to foundation profiles.

3.4. Design of formwork segments

After the design of concrete cross-sections, reinforcement, and connections was accomplished, the formwork 3D geometries for 3D printing, presented in Section 1.2, were generated. The formwork was modeled using the same volumetric modeling approach in the Rhino/Grasshopper 3D environment that enabled the creation of watertight mesh, including segmentation to fit into the 3D printer, positioning inlays for reinforcement and connectors, and all other necessary helpers for casting (Figure 7c). Finally, the formwork geometries were sliced, the printing and drying routines were computed, and the machine code was compiled and sent to the 3D printer for production.

4. Conclusion and outlook

This paper presents the structural design and analysis of a lightweight concrete structure—Marinaressa Coral Tree—produced using water-soluble sand formwork. The possibilities of the fabrication method allowed us to explore the potential of alternative morphologies of lightweight concrete structures, particularly spatial lattice and multiscale structures known for their unusual combination of lightness and strength. With this approach, the structure, representing a reinterpretation of the classical slab-to-column transition zone, was optimized regarding material distribution, and modeled as a spatial lattice oriented along the principal stress trajectories (Figure 8). Thus, it was possible to reduce the weight of the structure by 60 % in comparison to a solid concrete construction with the same load-bearing capacity.

The project presents an approach to the design of lightweight structures in the realities of climate change. It shows that the integration of design and production activities aimed at reducing structure's total ecological footprint should become the new measure of the “lightness” of design solutions and essential for future-proof construction approaches. In this context, the development of new sustainable production methods can, in turn, give a new impetus to structural design, opening opportunities for the emergence of new structural aesthetics. In addition, as concrete remains a generous construction material when it comes to the freedom of architectural forms, resolving a traditional problem of a complex and expensive formwork while achieving the necessary sustainability goals will open new horizons in the architectural and construction practice.

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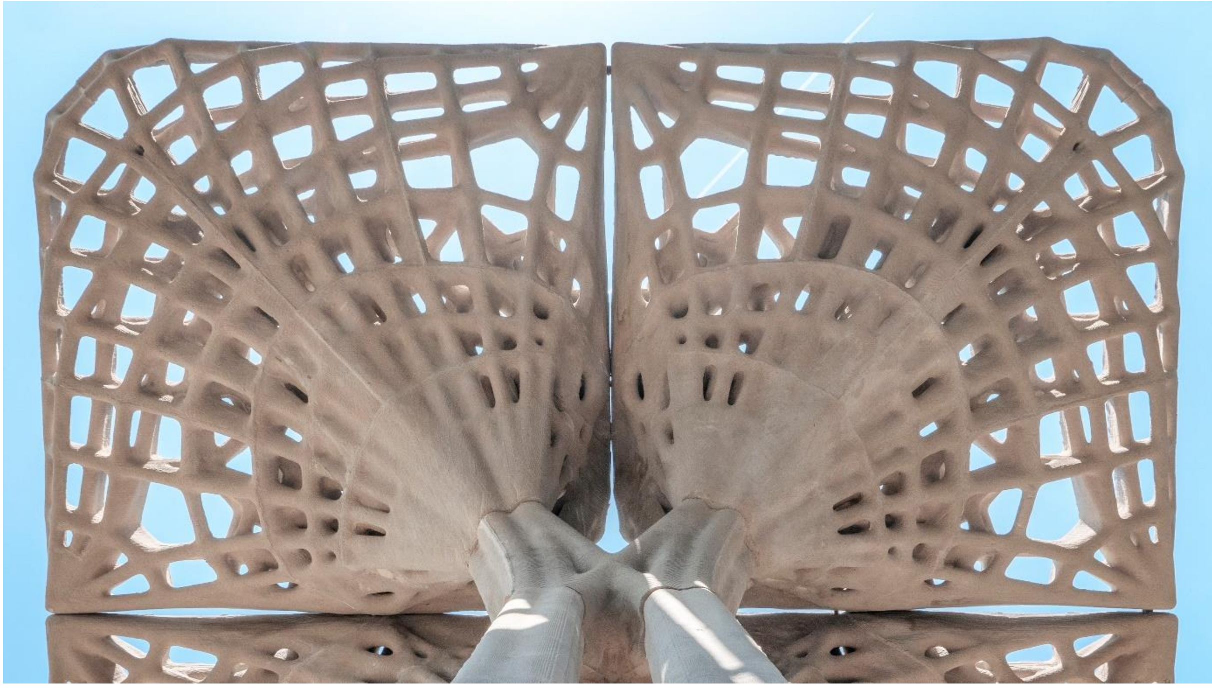

Figure 8: Close-up view of the Marinaressa Coral Tree from the bottom upwards.

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