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Kariouh, A., Lorenzen da Silva, V., Christidi, N., Brandt, N., Popescu, M., & D'Acunto, P. (2026). Necto: Structural design and engineering of a CNC-knitted membrane structure. *Structures*, 91, Article 112667. <https://doi.org/10.1016/j.istruc.2026.112667>

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Necto: Structural design and engineering of a CNC-knitted membrane structure

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ARTICLE INFO

Keywords:

Structural design
Structural analysis
Form-finding
Force density method
Finite element analysis
CNC knitting
Membrane structures
Low-carbon footprint structures
Natural fibers

ABSTRACT

This paper presents *Necto*, a low-carbon CNC-knitted tensile membrane made from natural flax fibers and installed in the Corderie of the Arsenale at the 19th International Architecture Exhibition of the Venice Biennale. Suspended between four existing historic masonry columns and anchored to the floor at four additional points, the membrane forms a lightweight, form-active system within a protected heritage environment. Its functionally graded knit architecture aligns flax fiber inlays and density variations with the two principal stress directions, yielding a material-efficient and biodegradable structure. The structural design combines physics-based form-finding refined through the Force Density Method, nonlinear Finite Element Analysis for prestress calibration and boundary cable sizing under Eurocode-based load combinations, and detailed verification of all structural interfaces—including anchored ground supports, non-invasive clamped column supports with pressure-distributing layers, and a ring support that distributes the membrane stresses at the funnel over eight suspension cables. By treating form-finding, analysis, detailing, fabrication, and assembly as mutually informing constraints, *Necto* demonstrates how a multi-fidelity structural design process can deliver a full-scale CNC-knitted membrane within a protected heritage context.

1. Introduction

Necto is a full-scale demonstrator exhibited as part of the 19th International Architecture Exhibition at the Venice Biennale [1]. The installation is located in the Corderie of the Arsenale, and remained on display from May to November 2025. *Necto* draws on classical physical form-finding precedents, particularly Antoni Gaudí's hanging chain models [2] and Frei Otto's soap-film experiments [3]. In both cases, geometry emerges from equilibrium under self-weight and boundary conditions, producing efficient funicular forms dominated by axial forces. *Necto* translates these principles into a contemporary material system, demonstrating how form-active structures can be designed, fabricated, and constructed at full scale using CNC-knitted textile technologies [4].

The demonstrator consists of a knitted membrane suspended between four existing historic masonry columns with a center-to-center

spacing of 6.9 m and 7.0 m. Fig. 1 shows the plan and elevation of the membrane structure, providing the overall dimensions of the installation. The 100 m² membrane is designed using computational structural design and optimization techniques, and fabricated using natural fibers. Functional grading aligns with principal force flows. The two principal stress directions are materialized as flax fiber inlays in one direction and density variations within the knit architecture in the other. The result is a material-efficient, lightweight and biodegradable structure that weighs 38.5 kg.

This paper presents the structural design, analysis, and realization of *Necto* as a case study for full-scale CNC-knitted membrane structures. This paper aims to provide a transferable reference for the structural engineering of low-carbon, knitted-textile architecture at building scale, and to make explicit the steps required to bring such a system from a form-finding model to a built installation.

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<https://doi.org/10.1016/j.istruc.2026.112667>

Received 15 March 2026; Received in revised form 5 June 2026; Accepted 14 July 2026

Available online 3 August 2026

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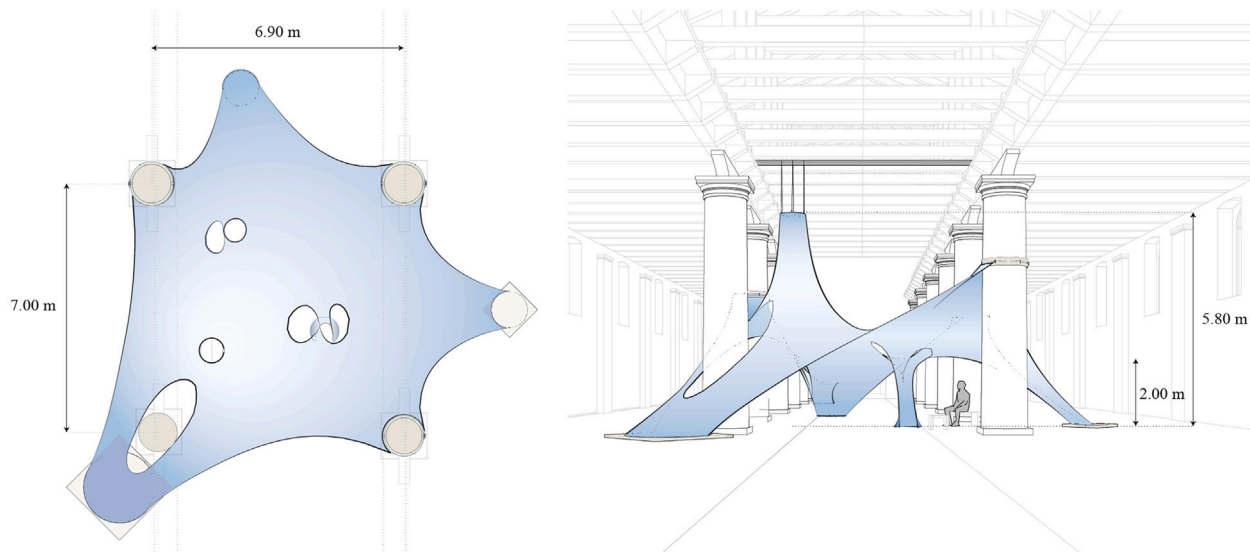


Fig. 1. Plan and elevation of the Necto membrane.

2. Background

Membrane structures carry load through geometry and membrane stresses rather than bending resistance, enabling lightweight constructions with reduced material use, making them well suited for temporary, adaptive, and resource-efficient architectural applications [5,6]. For structurally efficient membrane systems, the geometry and material layout ideally follow the internal force flow, leading to spatially differentiated stress distributions that minimize material use while maintaining equilibrium.

Advances in computational structural design enable numerical form-finding [7,8], analysis, and optimization [9] of membrane structures under complex boundary conditions, material anisotropy and nonlinear behavior, substantially expanding the range of feasible membrane geometries. Equilibrium-based methods, most notably the Force Density Method (FDM) [10] and Dynamic Relaxation (DR) [11], derive funicular geometries directly from a prescribed topology and a set of equilibrium parameters (e.g., force densities) and remain widely used for their numerical robustness and their direct interpretability in terms of internal forces. Combinatorial Equilibrium Modeling (CEM) [12] generalizes this equilibrium-based paradigm by coupling graph-theoretic topological diagrams with vector-based graphic statics, enabling structures composed of combinations of tension and compression members to be form-found from a prescribed combinatorial state of equilibrium. Continuum-based form-finding formulations embedded in nonlinear finite element frameworks, such as the Updated Reference Strategy [13], extend these approaches by incorporating anisotropy and prestress states, enabling tighter coupling between the resulting geometry and its predicted structural response. More recently, machine learning and differentiable programming approaches have added a further set of tools, including neural network-driven form-finding of compressive shells under combined vertical and horizontal loads [14], gradient-based constrained form-finding of tension–compression structures enabled by automatic differentiation [15], and E(3)-equivariant physics-based graph neural networks for generalized inverse form-finding [16]. Collectively, these developments broaden both the geometric and material design space available for membrane structures.

Despite these developments, the construction of non-standard membrane geometries remains challenging. Architectural membrane systems are typically fabricated from planar rolls of coated woven fabric with uniform patterns and structural properties. For complex doubly curved geometries with integrated functional details like channels and

openings, extensive cut-and-sew processes are necessary [17–20]. This restricts the potential geometric complexity and limits local control of material properties. These constraints become critical when attempting to realize structurally optimized geometries that rely on differentiated stress distributions and geometry-induced force flow.

CNC knitting technologies expand the design and fabrication potential of architectural membrane systems by enabling seamless, three-dimensional textiles with locally programmable properties [4,21].

Features such as channels, pockets, and openings can be directly integrated into the textile during production. These integrated details are often used to guide additional structural elements like cables and bending-active splines through the fabric, which function as shaping elements. This logic has been used in various implementations serving both architectural and structural purposes [4,22–25].

CNC knitting also makes it possible to design textiles with spatially differentiated material properties through variations in stitch patterns, yarn types, and stitch densities, facilitating graded behavior such as locally controlled deformation [26–28], stiffness distribution [29], and porosity [30] in response to geometric or structural requirements.

Continuous reinforcement in the form of inlays can be directly integrated into the knitted textile. Inlays are additional straight yarns inserted into the textile during the knitting process, without forming stitches themselves. This allows reinforcement fibers, such as high-strength yarns, glass fibers, or carbon fibers to be embedded during fabrication, tightly integrating structural performance with the textile production process [4,31].

Research on the computational structural design of CNC-knitted architectural membranes has established a range of workflows in which computational methods simulate the global shape behavior of these structures using low-fidelity equilibrium models based on FDM and DR. By representing the membrane as a network of tensioned linear elements, these models can be configured so that the mesh corresponds directly to the stitch architecture of the textile. This representation allows designers to control and modify individual stitches, or groups of stitches, or parameters related to the individual or groups of stitches (e.g., force density), which is particularly advantageous when working with knitted textiles that incorporate gradient patterns or spatial material differentiation. Furthermore, using a mesh that reflects the actual stitch distribution provides more informative feedback during analysis, as local geometric changes can be directly related to the underlying knitting logic. Such approaches have proven effective in capturing

the characteristic deformation behavior of differentiated knitted textiles, where local stiffness variations influence the resulting geometry [32–35].

However, when the structural response of these systems under applied loads must be evaluated, higher-fidelity numerical models become necessary. Finite Element (FE) models allow the explicit specification of material parameters, (an)isotropic constitutive behavior, and prestress magnitudes, enabling a more detailed assessment of deformation and stress development. Such approaches provide the analytical resolution required to evaluate load-bearing performance and identify critical stress concentrations that cannot be captured through simplified equilibrium representations.

Previous studies have presented workflows that integrate Finite Element Analysis (FEA) with form-finding simulations to develop a multi-scalar design methodology. In these workflows the structural topology is fixed while material parameters and force distributions remain adjustable to iteratively refine the geometry of textile hybrid structures [36]. Building on this foundation, subsequent research has demonstrated how FEA can be combined with textile differentiation strategies by linking simulated deformation patterns and axial stress distributions to stitch-based material variations [26,27].

Multi-fidelity modeling strategies have been widely explored in other areas of digital fabrication, particularly in computational workflows for additive manufacturing [37,38]. These approaches combine reduced-order models for rapid design iteration with higher-fidelity simulations for performance validation. Comparable frameworks, however, have not yet been systematically developed for CNC-knitted membrane structures.

Multi-fidelity modeling strategies have been widely explored in other areas of digital fabrication, particularly in computational workflows for additive manufacturing [37,38], where reduced-order models for rapid design iteration are combined with higher-fidelity simulations for performance validation. Preliminary steps in this direction have also been taken in the context of CNC-knitted textile structures [39]. However, a systematic multi-fidelity framework that links low-fidelity equilibrium models, high-fidelity FE analysis, and the actual knit logic of an architectural-scale, structurally loaded CNC-knitted membrane has not yet been established.

In the design of *Necto*, a multi-fidelity modeling strategy is adopted to combine the strengths of both modeling paradigms. Low-fidelity equilibrium models are first employed to establish the global geometry of the membrane structure and to estimate appropriate prestress states that define the equilibrium form. Subsequently, high-fidelity nonlinear FE models are introduced to evaluate the structural response of the resulting configuration under applied loading conditions.

3. Methodology

The final built structure (Section 7) is the result of its geometric design (Section 4), structural analysis (Section 5) and detailed design (Section 6), which are inseparable and reciprocal design drivers. Thus, design must be approached with an iterative co-design process [41] that integrates these interdependent constraints (Fig. 2).

3.1. Co-design methods

The geometric design (Fig. 2(a)) starts with an initial concept design step (Fig. 2(b)), as described by Lorenzen da Silva et al. [40]. After defining an initial design that satisfies the architectural requirements, a discrete equilibrium representation of the structure is generated using FDM (Fig. 2(c)). This approach quantifies the internal prestress distribution within the structure. Once the final form-found configuration is established, the global model is transferred to the FEA-software Dlubal RFEM 6 [42] for prestress and cable cross-section optimization (Fig. 2(d)). In the structural analysis step (Fig. 2(d)), different accidental load cases are analyzed to ensure structural safety throughout the service life of the structure.

In the detailed design step (Fig. 2(e)), all structural and architectural details, including the ground supports (Section 6.1), column supports (Section 6.2), and funnel support (Section 6.3) are dimensioned and modeled. The detailed models are analyzed using both FEA and analytical calculations to ensure adequate load-bearing capacity.

3.2. Finite element assumptions

Both the prestress and cable cross-section optimization step and the subsequent structural analysis step (Fig. 2(d)) are carried out under a consistent set of modeling assumptions, summarized in Table 1.

The membrane is represented by a quadrilateral mesh of cable elements that transfer axial forces only, consistent with the tensile surface idealization introduced in Section 3.4. The boundary cables are also represented as one-dimensional tension-only elements connected to the membrane mesh along its free edges. The geometry and internal force distribution obtained from the FDM form-finding step are imported directly into the FEA model, with the resulting member forces assigned as the initial prestress state, ensuring continuity between the form-finding and analysis stages. All ground, column, and funnel connections are idealized as pinned supports, transferring forces but no moments, in accordance with the detailing strategy presented in Section 6. External actions are applied as static load cases, neglecting dynamic and time-dependent effects, which are considered admissible given the temporary nature of the installation and the load scenarios examined.

3.3. Design constraints

The design workflow is shaped by assembly constraints imposed by the historic context of the Arsenale site. These constraints are not introduced retrospectively but are integrated from an early stage, informing the form-finding, structural analysis, and support detailing.

The column support design is governed by the limited load-bearing capacity and material fragility of the three existing historical masonry columns to which they are attached. Each column is coated with a layer of ancient lime mortar that cannot be damaged or locally overstressed. The maximum allowable surface load for the lime mortar is 0.69 MPa [43]. This requirement imposes strict limitations on both the maximum allowable reaction forces and the detailing of the support interfaces. These constraints are explicitly considered in the structural analysis, thereby defining upper bounds on the admissible loads transferred to the columns.

In addition to the column supports, the ground supports are subject to limitations imposed by the load-bearing capacity of the Arsenale floor. The maximum allowable surface loads are 7 kN/m² in areas with stone flooring and 3 kN/m² in areas with wooden flooring. These limits constrain both the size and positioning of supports, as well as the redistribution of forces within the structural system.

Collectively, these assembly-related constraints play a decisive role in shaping the global load paths, support configurations, and admissible prestress levels of the structure.

3.4. Material properties

The structural system consists of two primary material groups: the knitted membrane and the boundary cable system. Each material is selected and modeled according to its specific structural role, with material behavior (Tables 2 and 3) directly informing the low-fidelity and high-fidelity analysis stages.

The membrane is a bespoke textile consisting of a knitted fabric reinforced with straight, integrated inlays that act as the primary load-carrying elements. The knit is produced from a processed flax fiber (linen) yarn, while the inlay reinforcement is a bundle of two untwisted flax ropes—an 800-tex and a 600-tex yarn [44]—held together by a cotton wrapping, yielding a total linear density of 1400 tex. Flax fiber is selected for its favorable tensile performance, low embodied energy, and biodegradability. The inlays follow the principal stress directions identified using a custom stress trajectory tracer developed by Brandt

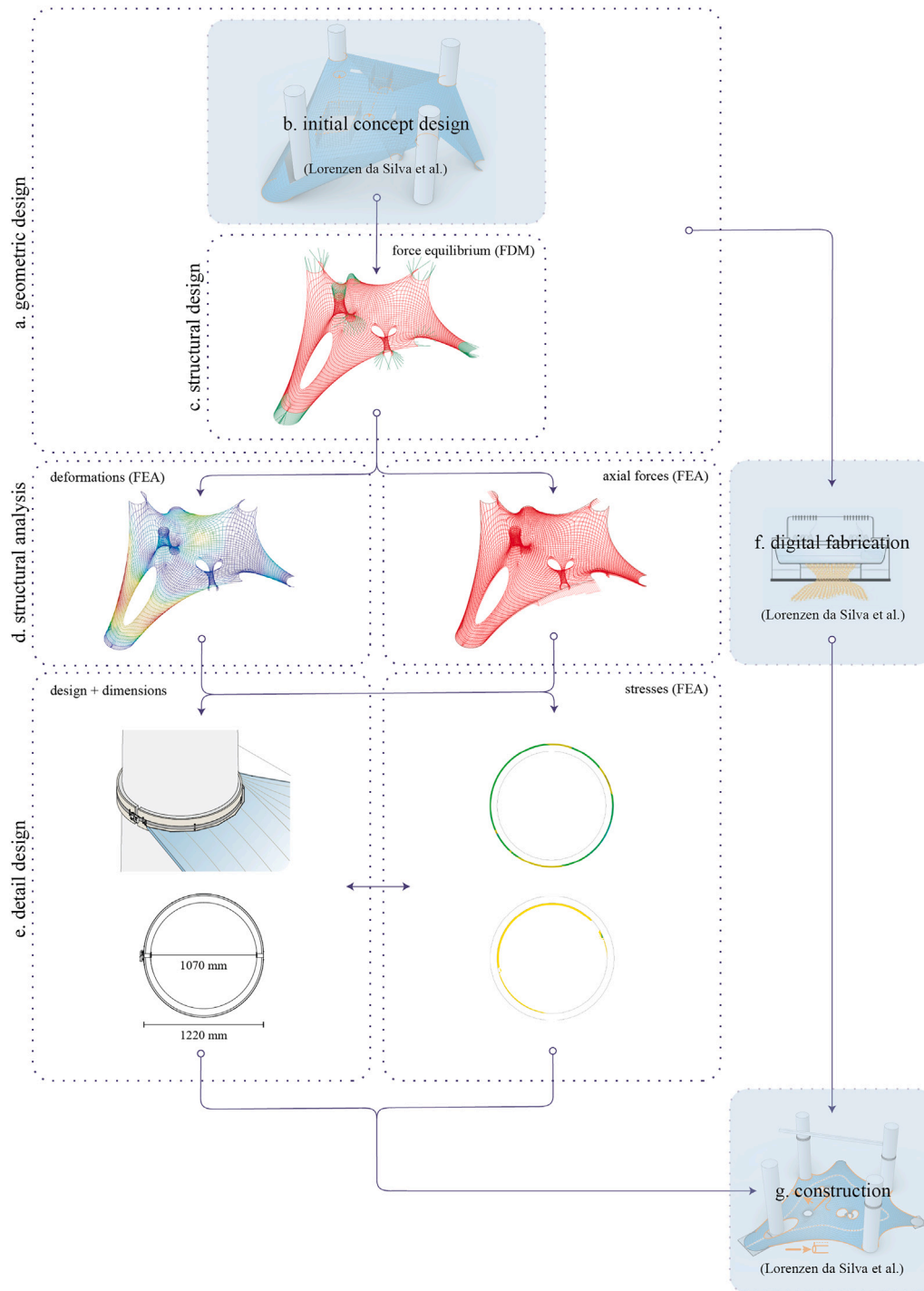


Fig. 2. Workflow of the co-design process, comprising (a) geometric design, (b) initial concept design, (c) structural design, (d) structural analysis, and (e) detailed design, and illustrating their integrated relationship with (f) digital fabrication and (g) construction processes, as presented in [40].

Table 1

Summary of finite element modeling assumptions for the prestress and cable cross-section optimization and the structural analysis.

Assumption	Setting
Element type	Cable element (in-plane tensile forces only, no bending stiffness)
Mesh definition	Structured quad mesh adopted from FDM step
Prestress initialization	Assigned stress based on FDM results
Support conditions	Pinned supports
Load application	Static

et al. [45], thereby providing directional tensile reinforcement where it is structurally most effective. The knit is formed from interlocking loops that can stretch substantially under load, as the loops unfold and rearrange before the fibers themselves are engaged. The inlays, in contrast, are straight yarns whose extensibility is limited to the intrinsic strain of the flax fibers. As a result, the in-plane stiffness of the membrane is governed by the inlays, with the knit functioning primarily as a support system that holds them in place. The mechanical properties of the inlays are taken directly from the yarn data provided by the manufacturer (Table 2).

Table 2

Mechanical properties of flax fiber yarn used for the inlays, according to the manufacturer [44].

Flax fiber			
Tensile strength of yarn	σ_t	N/mm ²	800
Young's modulus of yarn	E	N/mm ²	27 000
Density	ρ	kg/m ³	1 500

Table 3

Mechanical properties of the circular wire strand ropes, according to the manufacturer [46].

		10,820–0300	10,820–0400	10,820–0500
Diameter of wire rope	$\varnothing$ mm	3	4	5
Construction	—	6 × 7 + WC	6 × 7 + WC	6 × 7 + WC
Minimum breaking load	— kN	5.2	9.09	12.99
Design resistance force	F_{Rd} kN	3.47	6.06	8.66
Weight of wire rope	m kg	0.0298	0.0532	0.0882

The form-found mesh, adopted from Lorenzen et al. [40] and subsequently used in the FDM, is not aligned with the trajectories of the inlays. To maintain consistency between the force densities adopted in the FDM and the prestress values initialized in the FEA, this mesh is reused for the structural analysis; remeshing would have introduced discrepancies between the two stages. As a direct consequence of the mesh-inlay misalignment, the directional reinforcement provided by the inlays cannot be assigned on an element-by-element basis, and the textile is therefore modeled as an isotropic tensile surface. This averages the inherently anisotropic response of the reinforced knit.

The effective Young's modulus (E_0) of the membrane is derived from the inlays alone. The stiffness contribution of the surrounding knit is assumed to be negligible in comparison to that of the inlays. Consistent with the isotropic modeling assumption introduced above, the inlay stiffness is smeared uniformly over the membrane surface, and a reduction (safety) factor (γ) of 1.35 is applied to account for the misalignment between mesh edges and actual inlay directions. On this basis, the combined membrane system is represented in the model by an equivalent Young's modulus of 20 GPa.

The assumptions outlined above—neglecting the knit stiffness, smearing the inlay properties isotropically, and applying a global reduction factor (γ)—inevitably introduce uncertainty in the resulting equivalent membrane stiffness. To quantify the impact of this uncertainty on the structural response, a sensitivity study is presented in Section 5.1, in which the assumed equivalent Young's modulus is varied and its effect on the principal output quantities of the FE model—namely the membrane deformation and the axial stress in the

boundary cables—is assessed. These assumptions are also flagged as a limitation to be addressed in future work.

The boundary cable system consists of circular wire strand ropes of type 6 × 7 + WC (6 strands × 7 wires per strand, with a steel wire core in the center), manufactured from refurbished corrosion-resistant stainless steel by Jakob AG. The cables adhere to EN 12,385 / DIN 3053 standards. In the numerical simulations, the boundary cables are modeled as tension-only elements. The relevant geometric and mechanical properties are summarized in Table 3.

4. Geometric design

The geometric design process is subdivided into four steps: (i) a conceptual architectural design exploration, (ii) a low-fidelity form-finding workflow based on FDM, (iii) a transition from low- to high-fidelity representations, and (iv) a high-fidelity design workflow incorporating material behavior and geometric nonlinearity.

4.1. Initial design concept

The primary objective of the initial geometric exploration is to identify a geometric configuration that exhibits spatial articulation, expresses tensile action visually, and remains aesthetically compatible with the context of the Arsenal. At this stage, the design space is explored primarily with respect to qualitative geometric characteristics rather than precise structural performance indicators. The selected configuration represents a structurally coherent basis for subsequent analytical refinement.

Two modeling choices made at this stage are directly informed by the physical nature of the knitted membrane. First, a quadrilateral mesh topology is adopted, as its two orthogonal edge directions align naturally with the weft and warp directions of the knit and therefore provide a discretization that is consistent with the principal yarn orientations of the textile. Second, the anchor points are represented as pin supports, reflecting the physical behavior of the membrane at its connections: translations are fully restrained, while the absence of bending stiffness in the textile leaves rotations unconstrained. A detailed description of the meshing strategy, boundary conditions, design decisions, and the interactive design process is provided in [40].

4.2. Low-fidelity design workflow

Once a satisfactory geometric configuration is established, the workflow transitions from interactive exploration to a force-informed, low-fidelity form-finding approach based on FDM [10].

The aim of the low-fidelity design workflow is to derive a static equilibrium geometry that closely approximates the form obtained through

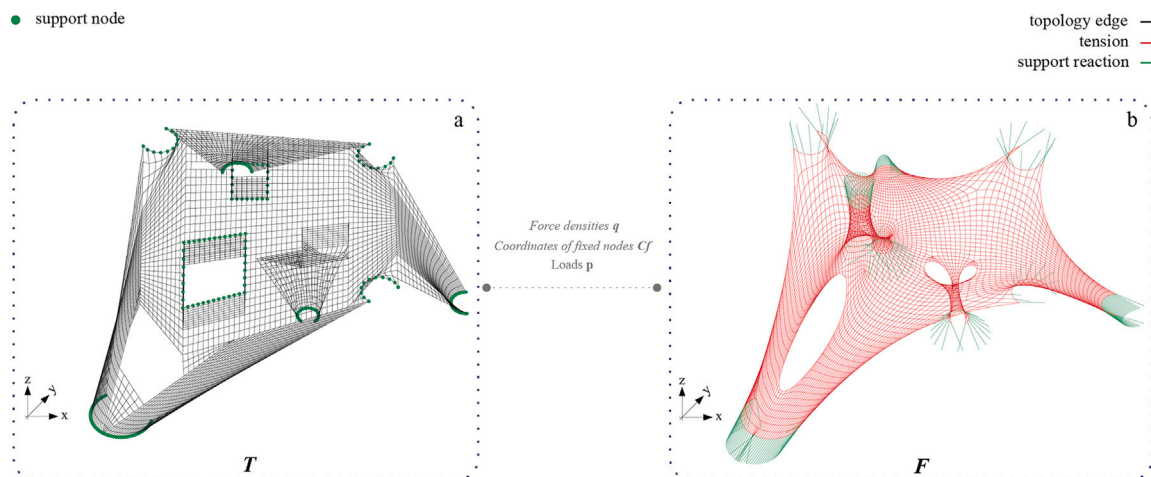


Fig. 3. Result of the FDM form-finding process, featuring a) the corresponding topology diagram T; and b) the form diagram F.

the initial exploration, while controlling internal force distributions. The resulting force density model (Fig. 3) serves as an intermediate representation, bridging intuitive geometric design and the subsequent high-fidelity structural analysis stages.

In the present workflow, the topology of the network and the location of the anchor nodes are inherited directly from the quadrilateral mesh defined during the conceptual design stage, so that the FDM acts exclusively on the free nodes by defining the force densities of the membrane edges and boundary cables. The force densities are treated as design parameters tuned to reproduce the target shape, and the resulting force ratios are subsequently transferred to the high-fidelity analysis as prestress values. This procedure is well-known in the literature as inverse form-finding or best-fit form-finding [16,47]. Force densities are tuned manually following two guiding criteria: (i) preserving the spatial articulation of the initial concept, in particular the curvature of the boundary cables and the relative position of the high and low anchor points; and (ii) ensuring that the resulting internal forces remain well within the strength capacity of the membrane and the boundary cables. This procedure is acknowledged to be heuristic; a more systematic, optimization-based treatment is discussed as future work in Section 8.2.

In the FDM framework, the structural system is represented as a network of axial elements, each characterized by a prescribed force density. To reflect the differentiated structural roles within the system, distinct force density values are assigned to specific element groups. The membrane edge elements are assigned a force density of 1 kN/m, representing the relatively flexible behavior of the knitted membrane while ensuring that the internal forces remain within the material's strength limits. In contrast, the boundary cables are prescribed a higher force density of 10 kN/m to reflect their greater axial stiffness along the perimeter, while still remaining below the cables' tensile strength capacity. This higher force density promotes load transfer to the boundary cables and reduces edge displacements of the membrane.

The resulting low-fidelity model therefore provides not only a statically stable geometry, but also a consistent set of relative force ratios within the boundary cable network. These force ratios serve as essential input for subsequent high-fidelity structural analysis and optimization stages, ensuring continuity between early-stage geometric exploration and detailed structural verification.

4.3. Low- to high-fidelity transition

While the low-fidelity FDM model efficiently reaches global equilibrium, it relies on simplified assumptions. Material behavior, geometric nonlinearity, prestress effects, and membrane–cable interaction are only implicitly represented. As a result, a transition to a higher-fidelity representation is required to verify structural performance and predict realistic deformations and stresses. This transition involves several key steps. First, the nodal coordinates and element connectivity obtained from the FDM model are imported into the FEA environment. Second, the elements are translated into a line-based representation suitable for finite element analysis. Third, the support nodes and support types are defined. Lastly, the relative force ratios derived from the prescribed force densities are converted into explicit prestress values.

4.4. High-fidelity design workflow

After importing the geometry into the FEA environment, material properties and initial prestress values are assigned to all structural members. For the membrane, the mechanical properties of the knit with inlays are adopted (Section 3.4). The boundary cables are initially modeled using steel wire rope type 10,820–0500 with a nominal diameter of 5 mm (Table 3).

The purpose of the high-fidelity workflow is to determine suitable boundary cable cross-sections and prestress magnitudes that satisfy prescribed deformation and internal force requirements.

Table 4

Load cases considered in the high-fidelity structural analysis.

Load case	Name	Description
LC1	Self-weight	Membrane and cable mass
LC2	Prestress	From form-finding and optimization
LC3	Accident I	100 kg person hanging on boundary cable
LC4	Accident II	100 kg person falling on membrane (location A)
LC5	Accident III	100 kg person falling on membrane (location B)

Table 5

Load combinations according to EN 1990, Annex A1.

Combination	Expression	Description
CO1	1.35 LC1 + LC2	
CO2	1.35 LC1 + LC2 + 1.5 LC3	Accidental scenario I
CO3	1.35 LC1 + LC2 + 1.5 LC4	Accidental scenario II
CO4	1.35 LC1 + LC2 + 1.5 LC5	Accidental scenario III

The structural verification and optimization procedures are based on a defined set of load cases and their corresponding combinations in accordance with EN 1990, Annex A1 [48]. Table 4 summarizes the individual load cases considered in the analysis.

The applied combinations are summarized in Table 5.

The first optimization step (Fig. 4(a)–(c)) focuses on minimizing the required membrane prestress while ensuring acceptable global deformation behavior under load combination CO1 (Table 5). A maximum allowable vertical displacement of 50 mm is imposed as a constraint in the optimization. This threshold is defined based on spatial requirements, ensuring sufficient clearance for visitors to pass beneath the structure while preserving the intended formal and architectural expression. For this prestress optimization stage, a conservative boundary cable diameter of 5 mm is adopted to eliminate cable capacity as a governing constraint and to isolate the influence of prestress magnitude on global deformation.

The optimization is performed iteratively. The process starts with a prestress distribution ranging from 4.23 N (minimum) to 1578.65 N (maximum), resulting in a maximum membrane deflection of 9.4 mm under CO1 (Fig. 4(a)). In the subsequent iteration, the prestress range is reduced to 0.42 N (minimum) and 157.87 N (maximum), leading to an increased maximum deflection of 42.2 mm (Fig. 4(b)). In the final optimization step, the prestress is further reduced to 0.04 N (minimum) and 15.79 N (maximum). This configuration results in a maximum deflection of 46.7 mm (Fig. 4(c)), thereby satisfying the prescribed deformation limit. The corresponding prestress distribution is therefore adopted for subsequent analyses.

Following the prestress optimization, a second optimization step (Fig. 4(d)–(f)) is conducted to minimize the required boundary cable cross-sections while maintaining adequate strength, stiffness, and serviceability under load combination CO1. In addition to structural safety, this step explicitly considers secondary objectives, including the reduction of overall structural mass, the minimization of forces transmitted to the funnel support, and the limitation of visual impact associated with oversized cable elements.

The optimization starts from the initial 5 mm circular wire strand rope (type 6 × 7 + WC, Table 3). The boundary cables are then systematically reduced in diameter and re-evaluated under CO1, while monitoring the governing response quantities, including peak axial cable forces, utilization relative to the rope resistance, global and local membrane deflections, and reaction forces transmitted into the funnel support. This parametric study shows that a 3 mm boundary cable provides an adequate balance between structural safety and stiffness while reducing cable mass and support reactions compared to the initial configuration. The results of the optimization are summarized in Table 6.

5. Structural analysis

The structural response of the membrane system is quantified under two complementary analyses: (i) a sensitivity study on the assumed

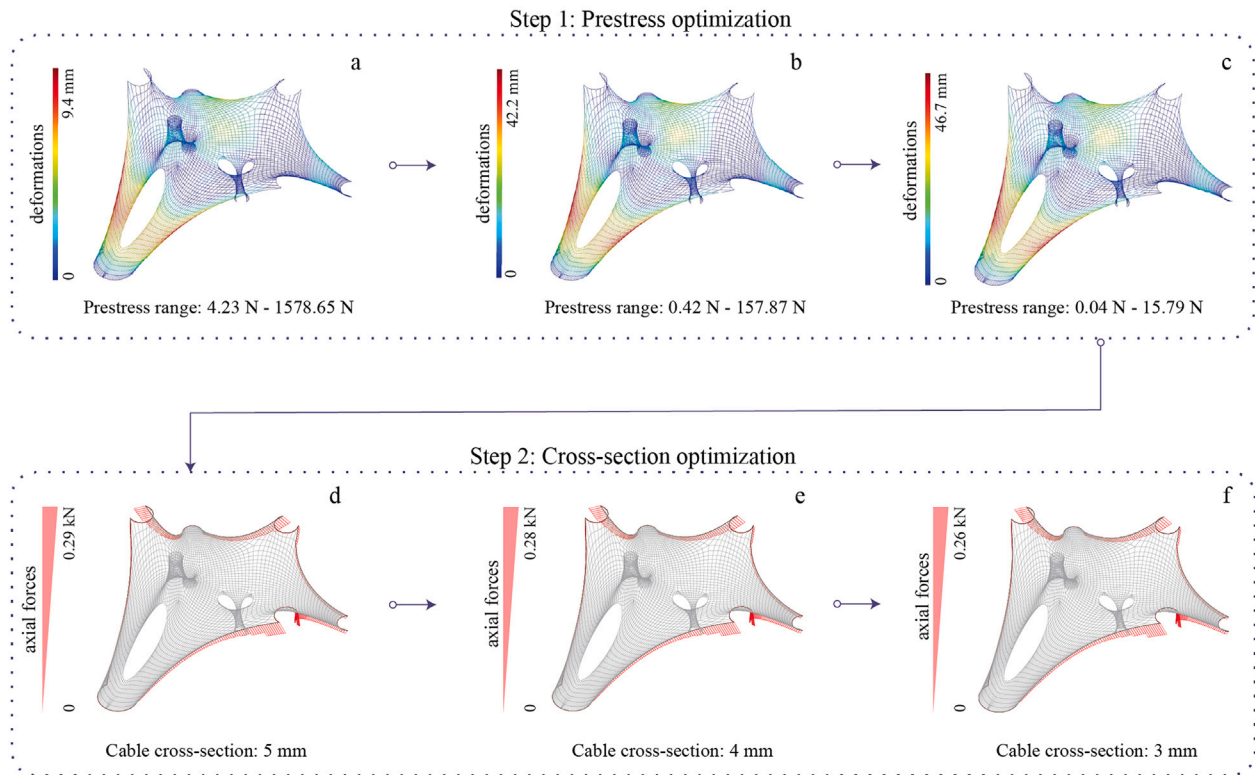


Fig. 4. FE results from the optimization process, consisting of: (I) prestress optimization, with (a) deformation δ for prestress distribution I (4.23 N to 1578.65 N), (b) deformation δ for prestress distribution II (0.42 N to 157.87 N), (c) deformation δ for prestress distribution III (0.04 N to 15.79 N), (II) cable cross-section optimization, with (d) axial forces in the boundary cables with a 5 mm cross-section, (e) axial forces in the boundary cables with a 4 mm cross-section, (f) axial forces in the boundary cables with a 3 mm cross-section.

Table 6

Structural response for different cable diameters.

Parameter (cable diameter)		3 mm	4 mm	5 mm
Boundary cable mass	kg	2.2	4.0	6.2
Total mass	kg	67.9	69.6	71.9
Force at funnel	kN	1.34	1.39	1.42
Max. deflection in z-direction u_z	mm	37.3	36.3	36.9
Max. absolute deflection u	mm	43.3	44.2	46.3
Cable force	kN	0.26	0.64	1.46
Cable strength	kN	3.47	6.06	8.66

membrane stiffness under the design load case (CO1), and (ii) an assessment of the system's behavior under accidental visitor-induced loads (CO2–CO4), with particular attention to the risk posed to the historic Arsenale fabric.

5.1. Sensitivity study

The equivalent Young's modulus of the membrane is derived analytically in Section 3.4 rather than measured directly, and the resulting estimate carries three residual sources of uncertainty: the assumption that the knit contributes negligibly to the in-plane stiffness compared to the inlays, the isotropic smearing of the inlay stiffness over a mesh that is not aligned with the inlay trajectories, and the magnitude of the reduction factor applied to account for this misalignment. To quantify the influence of this uncertainty on the principal output quantities of the FE model, a one-at-a-time parametric sensitivity study is conducted in which the membrane Young's modulus is varied while all other material and geometric parameters are held constant.

The sweep is bounded on the lower side by $0.5E_0 = 10$ GPa, a conservative case in which the knit contribution to the combined stiffness is overestimated by a factor of two, and on the upper side by

Table 7

Maximum membrane deflection and peak axial force in the boundary cables obtained from the parametric sweep on the membrane Young's modulus, under load combination CO1.

	$0.5 E_0$	$0.75 E_0$	E_0	$1.25 E_0$	E_{FINALIN}
Young's modulus E [GPa]	10	15	20	25	27
Maximum deformation δ [mm]	56.9	50.8	47.0	44.3	43.4
Maximum axial force N [kN]	0.23	0.25	0.28	0.30	0.31

$E_{\text{FINALIN}} = 27$ GPa, the stiffness of the inlay material itself and therefore the theoretical maximum attainable by the combined membrane under a rule-of-mixtures argument. Five discrete points are evaluated: $0.5E_0$, $0.75E_0$, E_0 , $1.25E_0$, and E_{FINALIN} , corresponding to 10, 15, 20, 25, and 27 GPa. For each point, the full FEM analysis is re-run under identical loading and boundary conditions, and the maximum membrane deflection δ and the peak axial force N in the boundary cables are extracted. The results are summarized in Table 7 and Fig. 5.

To normalize the influence of the membrane stiffness on the structural response, a dimensionless sensitivity coefficient is computed for each output Y as $S_Y = (\Delta Y/Y_0)/(\Delta E/E_0)$, where Y_0 and E_0 denote the values at the nominal operating point. A coefficient of $|S_Y| \approx 1$ indicates proportional scaling with E ; $|S_Y| \ll 1$ indicates near-insensitivity. The resulting values are reported in Table 8.

Across the considered range, $|S_\delta|$ lies between 0.22 and 0.42 and $|S_N|$ between 0.29 and 0.43, indicating that both response quantities scale clearly sub-proportionally with the assumed stiffness. The signs are physically consistent: a stiffer membrane reduces its own out-of-plane deflection while shedding marginally more force into the boundary cables. The maximum deflection varies between -7.7% and $+21.1\%$ relative to the nominal case and the peak axial force between -17.9%

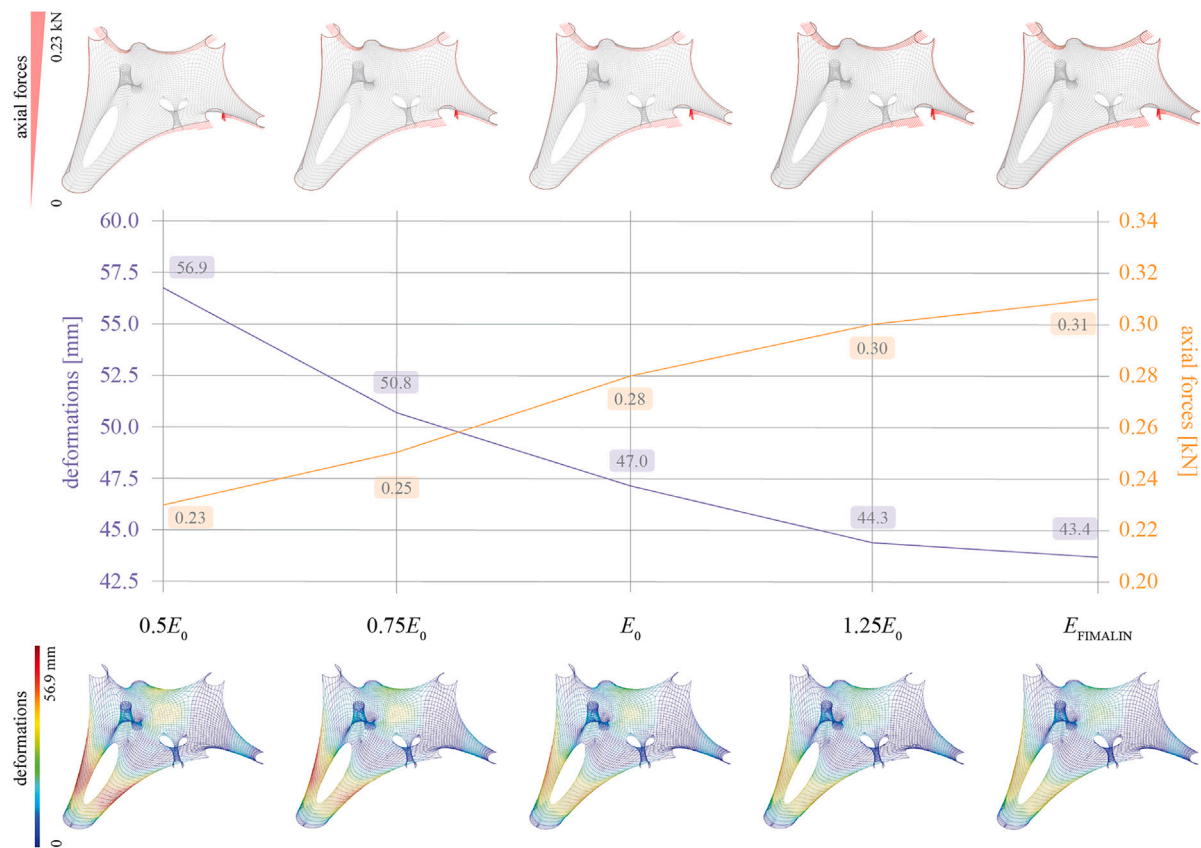


Fig. 5. Sensitivity of the structural response to the assumed membrane Young's modulus under load combination CO1: (a) maximum membrane deflection δ as a function of E ; (b) peak axial force N in the boundary cables as a function of E . Markers indicate the five evaluated points; the nominal operating point $E_0 = 20$ GPa is highlighted.

Table 8

Dimensionless sensitivity coefficients of the maximum membrane deflection (S_δ) and the peak axial force (S_N) with respect to the membrane Young's modulus, evaluated at each non-nominal point of the parametric sweep.

	$\Delta E/E_0$ [–]	S_δ [–]	S_N [–]
$0.5 E_0$	–0.50	–0.42	0.36
$0.75 E_0$	–0.25	–0.32	0.43
$1.25 E_0$	+0.25	–0.23	0.29
E_{FINALIN}	+0.35	–0.22	0.31

and +10.7%; these variations do not alter the qualitative conclusions of the structural assessment, and the design criteria remain satisfied throughout. A dedicated experimental characterization of the bespoke flax knit, beyond the scope of the present project timeline, would allow this residual uncertainty to be eliminated.

5.2. Response under accidental loads

Having established in Section 5.1 that the predicted response varies only mildly with the assumed membrane stiffness, the same FE model is now exercised under the accidental load combinations CO2, CO3, and CO4. Building on the prestress magnitudes and boundary cable dimensions fixed in the preceding sections, a global nonlinear structural analysis is conducted to verify overall stability and to assess the risk of damage to the historic fabric of the Arsenale during the use phase.

The accidental combinations represent concentrated, non-design interaction loads caused by visitors to the exhibition. Specifically, CO2 corresponds to a person hanging from a boundary cable, while CO3 and CO4 represent a person falling onto the membrane at two distinct locations. All analyses are conducted using a geometrically nonlinear FE model,

accounting for large displacements, membrane–cable interaction, and the stiffness contribution of the prestress state.

For each scenario, the accidental action is introduced as a localized vertical load applied over a defined contact area, as illustrated in the upper row of Fig. 6. The locations and extents of the loading areas are selected to represent conservative but plausible visitor interactions, ensuring that critical response regions of the system are captured.

The resulting deformation fields for CO2, CO3, and CO4 are shown in the middle row of Fig. 6. All cases exhibit significant local deformations of the membrane surface in the vicinity of the applied load. The tensile system remains stable throughout the simulations, with no numerical instabilities or loss of equilibrium. However, the resulting displacement magnitudes are substantially larger than those obtained for the fundamental design combination CO1.

The lower row of Fig. 6 presents the corresponding axial forces in the boundary cable elements. Compared to CO1, the accidental scenarios produce a pronounced amplification of cable forces, with peak tensile values occurring in cable segments adjacent to the loaded membrane regions. The increased cable forces are directly transferred to the supporting system, resulting in significantly higher reaction forces at the column supports. While both membrane and cable elements remained within their material capacity limits, the elevated support reactions are critical due to the vulnerability of the historic masonry columns and their lime mortar interfaces.

Table 9 presents a summary of the structural analysis results for the load combinations CO1, CO2, CO3, and CO4.

Based on the magnitude of the support reactions under CO2, CO3, and CO4, these accidental scenarios are assessed as posing an unacceptable risk to the surrounding historic fabric, despite the structural adequacy of the tensile system itself. The governing constraint is

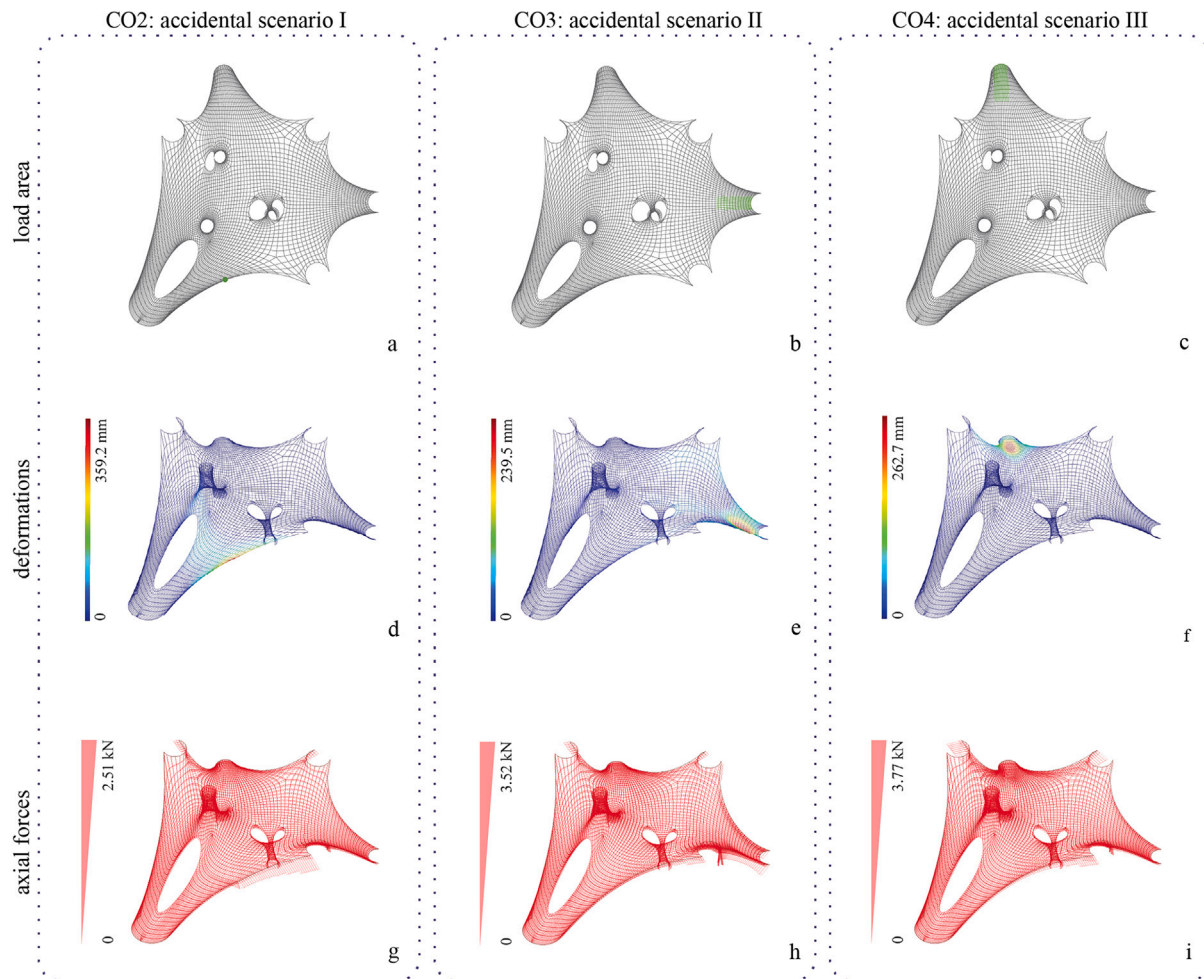


Fig. 6. Structural analysis results: (a) accidental scenario I CO2; (b) accidental scenario II CO3; (c) accidental scenario III CO4; (d) deformation δ for CO2; (e) deformation δ for CO3; (f) deformation δ for CO4; (g) axial forces in the boundary cables and membrane for CO2; (h) axial forces in the boundary cables and membrane for CO3; (i) axial forces in the boundary cables and membrane for CO4.

Table 9

Summary of structural analysis results for the load combinations CO1, CO2, CO3, and CO4.

	Maximum deformation [mm]	Maximum axial forces [kN]
CO1	46.7	0.26
CO2	359.2	2.51
CO3	239.5	3.52
CO4	262.7	3.77

the limited load-bearing reserve of the historic masonry columns and their lime mortar interfaces, which cannot safely sustain the amplified reactions without risk of cracking, joint opening, or progressive degradation of the column–anchor connection. Such exposure is incompatible with the principles of minimum intervention and reversibility that frame temporary installations in heritage contexts.

Several design modifications could in principle extend the admissible envelope to CO2–CO4: decoupling the tensile system from the substrate via an independent steel frame or ballasted masts; inserting force-limiting devices (mechanical fuses, friction-slip connectors, or yielding sacrificial links) at the cable-to-column interfaces; or redistributing reactions across additional anchor points and intermediate restraint cables.

Increasing prestress would reduce CO2–CO4 displacements but simultaneously raise baseline CO1 reactions, and is therefore not viable in isolation. None of these options is adopted here: an independent frame would compromise the architectural intent of visual lightness and direct dialogue with the existing fabric, while force-limiting devices and additional anchors would increase the footprint and visual intrusion on the historic columns, conflicting with the same minimum-intervention principles motivating the restriction. Given the temporary nature of the installation, the controlled visitor flow, and continuous supervision, operational restriction provides equivalent safety at markedly lower intervention cost on the heritage substrate, addressing residual risk through procedural rather than structural means.

Consequently, load cases LC3, LC4, and LC5 are excluded from permissible operational conditions, and on-site precautionary measures prevent visitors from hanging on, climbing onto, or otherwise applying unintended concentrated loads, ensuring that the system operates exclusively within the bounds of LC1.

6. Detailed design

Based on the resultant forces derived from the geometric design and structural analysis phase, the process is extended to the detailed design of the system. The primary objective of this phase is to ensure that all forces introduced by the structure are compatible with the historical

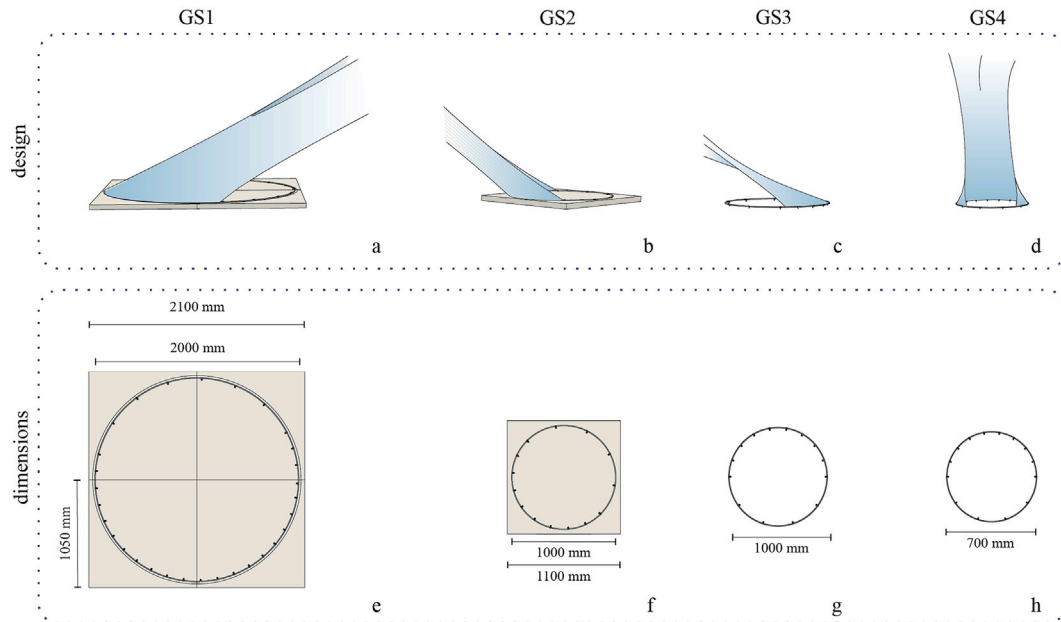


Fig. 7. Design and structural assessment of the ground supports GS1–GS4: (a–d) overall design configuration of ground supports; (e–h) corresponding geometric dimensions.

context of the site. Accordingly, the detailed design focuses on the development and verification of all critical interfaces between the tensile membrane system and the existing building. Given the lightweight nature of the membrane and the sensitivity of the building, particular attention is paid to load transfer mechanisms, material compatibility, and reversibility. Three principal detail elements are developed and analyzed: (i) ground supports, (ii) column supports, and (iii) the funnel support system at the apex.

6.1. Ground supports

The structure is supported at four discrete ground points, each designed to accommodate site-specific constraints related to the existing floor construction within the Corderie of the Arsenale. Fig. 7 gives an overview of the design and dimensions of the ground supports.

Ground supports (GS) 1 and 2 (Fig. 7(a),(b)) consist of repurposed *Giallo Dorato* marble stone plates that act as gravity-based anchoring elements. In these configurations, the tensile boundary cable is attached to a solid steel tube, which is mechanically secured to the stone plate using steel straps anchored directly into the stone. The marble has a specific weight of 2.1 kN/m^3 and is selected based on local availability, sufficient mass, and aesthetic compatibility with the site. The required thickness of the stone plates is determined based on equilibrium considerations, ensuring adequate resistance against both sliding and overturning under the governing load combinations obtained from the structural analysis.

Sliding resistance is verified by comparing the available friction force at the interface between the stone plate and the floor surface with the resultant horizontal force transmitted by the membrane system. The condition for preventing sliding is given by

$$F_h \leq \mu F_{sw} \quad (1)$$

$$F_h \leq \mu (W - F_v) \quad (2)$$

where F_h is the resultant horizontal force applied to the stone plate by the membrane, μ is the friction coefficient between the stone plate and the floor surface, W is the self-weight of the stone plate, acting at its barycenter, F_v is the resultant vertical force applied by the membrane, also assumed to act at the barycenter of the stone, and F_{sw} is the difference between W and F_v .

Overturning resistance is assessed by evaluating moment equilibrium about the critical rotation edge of the stone plate. The condition for preventing rotation is expressed as

$$M_{up} \leq M_{sw} \quad (3)$$

where M_{up} is the resultant overturning moment induced by the upward membrane load, and M_{sw} is the stabilizing moment due to the self-weight of the stone plate, both evaluated about the same reference axis, with the lever arm defined as the distance from the barycenter to the critical rotation edge.

For GS 1, the governing failure mode is sliding. F_h is 2355 N, while F_v is 1155 N. The required stone weight (W) to prevent overturning is 1705 N, corresponding to approximately 174 kg. Assuming a friction coefficient (μ) of 0.6 [49], a minimum stone weight of 3925 N or approximately 400 kg, is required to prevent sliding. This results in a minimum plate thickness of 41.2 mm for the given stone density. Based on the available standardized sizes, a stone thickness of 50 mm is selected.

For GS 2, sliding is likewise the governing failure mode. F_h is 793 N and F_v is 620.6 N. The required W to prevent overturning is 997 N, equivalent to approximately 102 kg. To prevent sliding, a minimum stone weight of 1320 N, corresponding to approximately 135 kg, is required when μ is 0.6. This leads to a minimum required plate thickness of 55.7 mm. A standardized stone thickness of 60 mm is therefore adopted.

In contrast, GS 3 and 4 (Fig. 7(c),(d)) are located in an area with a wooden floor system and therefore adopt a different anchorage strategy. Here, the solid steel tube is fixed directly into the underlying wooden structure, creating a more rigid and permanent connection. This approach ensures adequate resistance to the pull forces, induced by the membrane prestress, while respecting the load-bearing capacity of the wooden floor.

For GS 3 and GS 4, which were rigidly connected to the underlying wooden floor structure, the only relevant failure mechanism is pull-out of the anchoring system. GS 3 requires a tensile resistance of 2030 N, while GS 4 requires a tensile resistance of 978 N. The anchored ring supports used at these locations provide sufficient pull-out capacity to safely resist these loads, as confirmed by the corresponding structural verification.

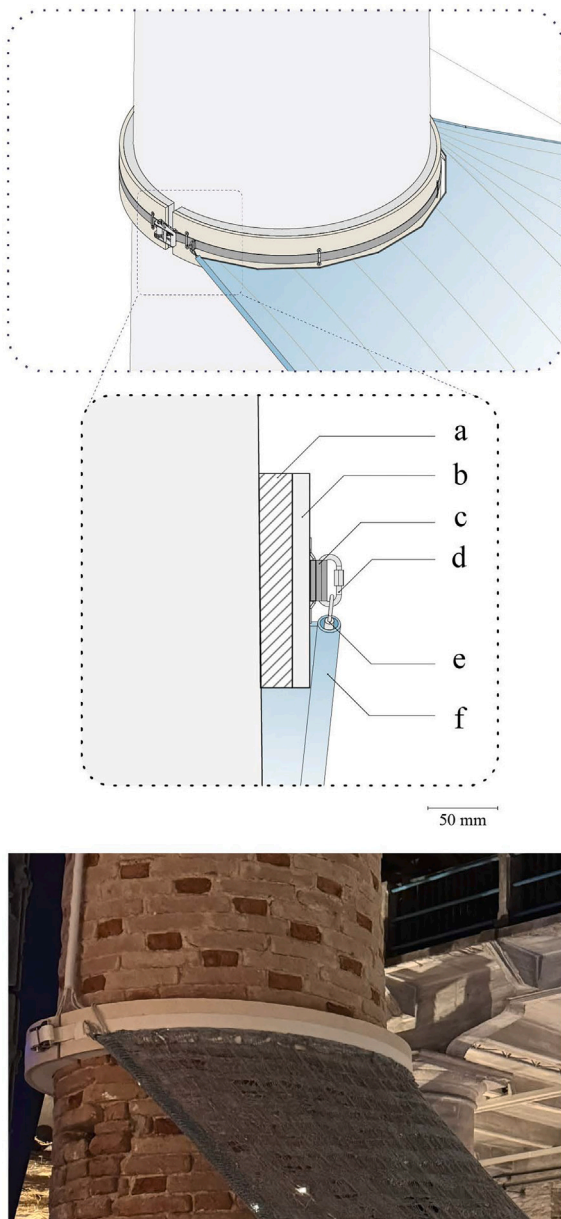


Fig. 8. Top: Closeup of the column support showing the clamping collar cross-section with (a) 50 mm-thick milled foam, (b) 16 mm-thick plywood collar, (c) ratchet strap loop, (d) threaded chain, (e) boundary cable, (f) integrated channel in the knit. Bottom: Final column support.

6.2. Column supports

The column support system (Fig. 8) is designed to transfer the membrane and boundary cable forces into the existing masonry columns in a safe, reversible, and noninvasive manner. The design avoids drilling or permanent modification of the historic fabric while ensuring stable anchorage under service loading. The primary aim is to prevent slippage and to minimize localized compressive stresses acting on the historic lime-mortar surface of the columns.

The anchorage is realized through a cylindrical clamping collar fabricated from 16 mm-thick plywood (Fig. 8(b)), which is assembled concentrically around each masonry column. The collar is tightened using a high-strength ratchet strap (Fig. 8(c)) which applies a controlled circumferential confining force to stabilize the system and generate frictional resistance. To minimize contact pressure on the masonry surface, the collar height is set to 150 mm, thereby maximizing the effective

bearing area and minimizing stress concentrations. An intermediate layer of 50 mm-thick milled foam (Fig. 8(a)) is placed between the plywood collar and the masonry to homogenize the contact pressure, accommodate geometric irregularities of the column surface, and mitigate local stress peaks. The tensile boundary cables (Fig. 8(e)) are connected via threaded chain connectors (Fig. 8(d)) which are securely stitched into the ratchet strap, providing a continuous and adjustable load path from the membrane boundary to the column interface.

The structural assessment of the column supports focuses on verifying safe and effective load transfer from the prestressed boundary cables to the masonry substrate without exceeding the compressive capacity of the lime mortar bedding. In addition, potential sliding and crushing failure modes at the interface are explicitly assessed through verification of frictional resistance and evaluation of the compressive stress distribution in the mortar layer. A nonlinear FEA is conducted considering load combination CO1 only, since accidental combinations (CO2-CO4) were identified as critical and excluded from permissible operation through on-site precautionary measures. The collar-masonry interface is modeled as frictional contact to represent shear resistance and no bonding is assumed at the interface to enforce compression-only interaction.

The normal stresses in the plywood collar induced by the circumferential force flow from the strap and cable anchorage are shown in Fig. 9(b). The stress distribution confirms a stable confinement mechanism and indicates that the applied forces are redistributed around the column perimeter without localized overstressing of the plywood collar.

The corresponding compressive stress distributions at the masonry interface are shown in Fig. 9(c-d). The maximum interface compressive stress is calculated as 10.6 kPa, which is significantly below the allowable mortar strength of 690 kPa [43]. This results in a utilization ratio of 0.02, confirming a substantial safety margin and validating the adopted support concept for operation under CO1.

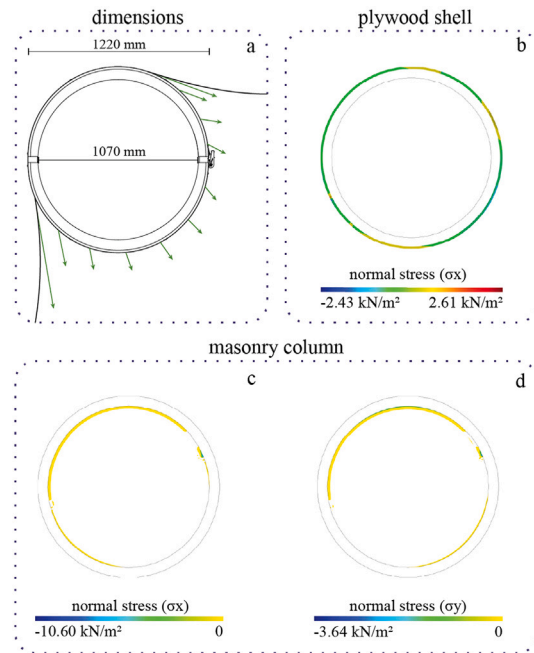


Fig. 9. Stress distribution in the plywood collar and at the masonry interface induced by the column support. (a) column and collar dimensions; (b) normal stress σ_x in the plywood collar due to axial forces of the boundary cables and membrane; (c) normal stress σ_x at the masonry surface due to the contact pressure of the column support system (plywood collar and foam layer); and (d) normal stress σ_y at the masonry surface resulting from the same contact pressure.

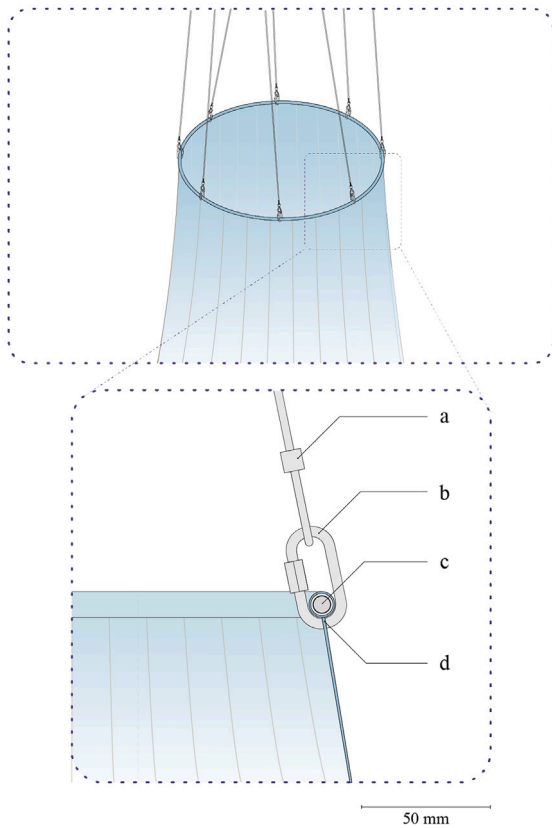


Fig. 10. Top: Closeup of the funnel support showing the ring cross-section with (a) the suspension cable, (b) threaded chain, (c) stainless steel compression ring, and (d) integrated channel in the knit. Bottom: Final funnel support.

6.3. Funnel support

At the apex of the membrane structure, the tensile forces converge into a funnel. The objective of the funnel support (Fig. 10) is to collect the circumferential membrane tension, redistribute it uniformly over a set of eight cables, and transfer it in a controlled manner to the overhead supporting beam.

A total membrane tension of 1.7 kN is collected by a solid stainless steel ring with a diameter of 8 mm (Fig. 8(c)), with grade EN 1.4436. The ring distributes the membrane forces and transfers them to eight radially arranged steel cables (Fig. 8(a)), which are hooked onto the ring using threaded chains (Fig. 8(b)). The cables act as the primary load-carrying elements connecting the membrane to the overhead supporting beam. The cables are the same 3 mm circular wire strand rope (type 6 × 7 + WC used for the boundary cables. This configuration ensures a symmetric force redistribution and provides geometric stability of the funnel region.

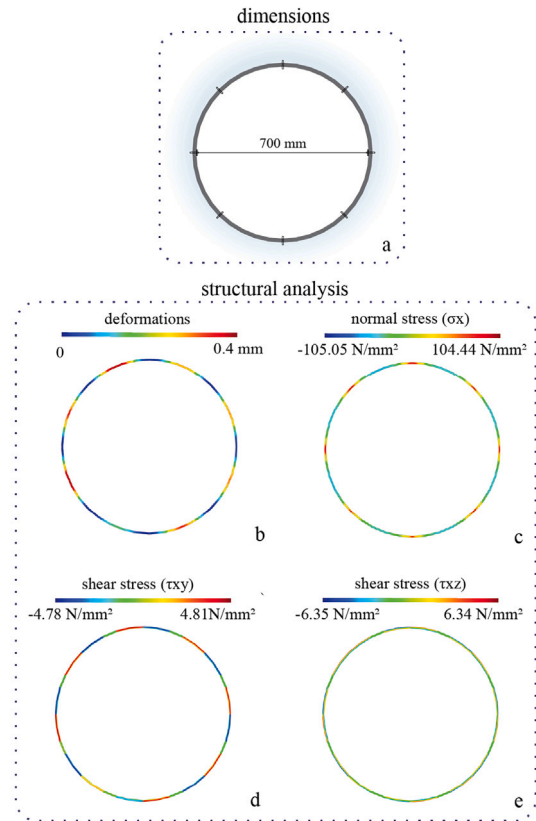


Fig. 11. Deformation and stress state of the ring subjected to uniform downward tension from the membrane and discrete upward forces from eight cables. (a) Dimension of the ring; (b) deformation δ of the ring; (c) normal stress in the ring resulting from the axial force σ_x ; (d) shear stress in the ring due to bending about the y -axis; and (e) shear stress in the ring due to bending about the z -axis.

The stainless steel ring is modeled as a continuous beam element subject to the resultant membrane forces, introduced as distributed circumferential loads to represent the membrane tension at the apex. The analysis provides the deformation (Fig. 11(b)), normal stress (Fig. 11(c)) and shear stresses (Fig. 11(d),(e)) in the ring under COI.

The maximum normal stress from axial force is 105.05 MPa, while shear stresses remain below 6.34 MPa. These values are well below the allowable stress limit of 220 MPa for EN 1.4436 stainless steel. The maximum ring deflection is limited to 0.4 mm. The maximum tensile force in the apex cable system is 0.238 kN, which is significantly lower than the cable capacity of 3.47 kN. The results confirm that both the ring and the cable system satisfy the required strength and serviceability criteria with substantial safety margins.

The funnel support system is suspended from a steel beam spanning 7.0 m between two opposing balconies in the Corderie. The beam has an SHS 100 × 2 cross-section fabricated from S235JRH steel and provides the primary horizontal support for the apex assembly. The funnel ring is connected to the beam via eight stainless steel cables, introducing a resultant point load of 1.7 kN located 2.0 m from the left support. This eccentric loading induces combined bending and shear in the beam.

The beam is modeled as a simply supported member subjected to a single concentrated load. The resistance of the cross-section is verified according to Eurocode 3 (EN 1993-1-1) [50]. The condition for bending resistance is expressed as

$$M_{Ed} \leq M_{Rd} \quad (4)$$

where M_{Ed} is the design bending moment, and M_{Rd} is the design bending resistance of the cross-section.

Table 10
Material and section properties of the SHS 100 × 2 beam.

			SHS 100 × 2
Yield strength	f_y	MPa	235
Young's modulus	E	MPa	210,000
Elastic section modulus	W	cm ³	20.7
Second moment of area	I	cm ⁴	103.7
Cross-sectional area	A	cm ²	7.43

The shear verification is performed by comparing the design shear force with the design shear resistance of the section

$$V_{Ed} \leq V_{Rd} \quad (5)$$

$$V_{Ed} = \max(R_A, R_B) \quad (6)$$

where V_{Ed} is the design shear force, V_{Rd} is the design shear resistance, and R_A and R_B are the support reactions at the left and right supports, respectively.

Serviceability performance is assessed by evaluating the vertical deflection of the beam under the applied load. The serviceability requirement is expressed as

$$\delta_{max} \leq \delta_{lim} \quad (7)$$

where δ_{max} is the maximum deflection, δ_{lim} is the allowable deflection limit, typically taken as $L/250$ for beams supporting non-sensitive structural elements.

The material and geometric properties adopted in the verification are summarized in Table 10.

The verification confirms that the SHS 100 × 2 beam satisfies the requirements prescribed by Eurocode 3, demonstrating adequate resistance to the bending, shear, and deformation demands induced by the funnel support system.

7. From design to construction

The transition from computational design to physical realization is characterized by a tightly coupled workflow between digital modeling, material prototyping, and on-site assembly. Further details on the segmentation strategy and the broader interdependencies between digital design and fabrication are discussed in [40].

The knitted membrane is fabricated using a CNC knitting machine with a maximum production width of 1.8 m. This width limitation requires dividing the membrane into multiple longitudinal strips.

These strips are partially pre-assembled off-site to simplify construction on-site. The individual textile strips are joined along their edges by sewing, using a hand-held sewing machine, to form two large membrane assemblies while maintaining control over seam alignment and tolerances.

The on-site construction process follows a carefully defined sequence derived from the computational model and validated through mock-ups and pre-assembly tests. The installation begins with laying the two knitted textiles flat on the ground, allowing for visual inspection and verification of seam continuity and orientation.

At this stage, a modification to the originally specified cable system becomes necessary. Due to logistical constraints, the circular wire strand steel ropes defined in the construction documents are not available within the required timeframe. To maintain the project schedule without compromising structural performance, an alternative cable material is selected: a Kanirope Dyneema PRO rope, diameter 2 mm, 300 m length, 12-strand braided. This high-performance polyethylene (HMPE) rope provides a comparable tensile capacity to the originally specified steel cables, with a rated breaking load of approximately 4.1 kN, exceeding the 3.47 kN capacity of the steel ropes. The substitution is therefore structurally admissible within the prescribed safety factors, while introducing negligible modifications to the global force distribution predicted by the computational model.

Subsequently, the boundary cables (Kanirope Dyneema PRO rope), the stainless steel funnel ring, and the ground rings are guided through the integrated channels within the textile membrane. This step ensures the correct alignment of the load-carrying elements prior to the introduction of any significant prestress. The ground supports and column supports are then positioned according to the coordinates defined in the digital model, ensuring consistency between the designed and as-built geometry.

The assembly continues with the attachment of the membrane to the column supports, establishing the primary anchorage points while the structure remains largely unstressed. Following this, the funnel assembly is suspended from the overhead beam, activating the upper load path and allowing the membrane to gradually assume its three-dimensional shape. In the final stage, the remaining boundary conditions are engaged, and the membrane is progressively tensioned to reach the prescribed prestress state, ensuring that the final geometry matches the computational predictions.

Fig. 12 shows the final CNC-knitted membrane structure.

8. Discussion

Necto demonstrates the successful application of an integrated computational–structural workflow, using established form-finding and analysis methods, for the design and analysis of a full-scale CNC-knitted tensile membrane structure. By combining qualitative geometric exploration, low-fidelity form-finding, high-fidelity structural analysis, and detailed support design, the project establishes a clear proof of concept for bespoke knitted membranes as structurally active architectural systems.

8.1. Limitations

Several limitations of the adopted methodology must be acknowledged. At the global scale, the structure is modeled as a discrete network rather than as a continuous membrane in both form-finding and FEA. Although this approach efficiently captures the dominant tensile force paths, it neglects aspects of membrane behavior such as shear stiffness, local stress redistribution, wrinkling, and cable-membrane slippage. Consequently, the predicted stress states and deformations should be interpreted as conservative approximations.

In addition, to maintain consistency between the force ratios obtained from the FDM step and the prestress values implemented in the FEA, the mesh generated during form-finding is reused for the subsequent optimization and structural analysis. As this mesh does not represent the material directionality of the knit and inlays, the textile is modeled as an isotropic tensile surface, thereby averaging out its inherently anisotropic structural response. As a result, local variations in stiffness along the knit directions are not captured, and the computed stress distribution should be regarded as a homogenized estimate rather than a directionally resolved prediction.

A further limitation concerns the form-finding strategy itself. The FDM workflow adopted in this study is driven by geometric approximation of the initial architectural concept rather than by explicit structural performance criteria. Force densities are tuned manually to approximate the target shape, and no formal optimization is performed on either the network topology or the distribution of force densities. As a result, the equilibrium geometry obtained from the FDM step, although statically consistent and compatible with the strength capacity of the membrane and cables, is not guaranteed to be optimal with respect to mechanical objectives such as stress uniformity, deflection minimization, or material efficiency.

Similarly, the material behavior of the knitted textile is represented using approximated mechanical properties derived from the flax fiber yarn properties. While sufficient for structural verification at this stage, this approach does not fully capture the anisotropic, nonlinear, and time-dependent behavior of the bespoke knitted membrane. A

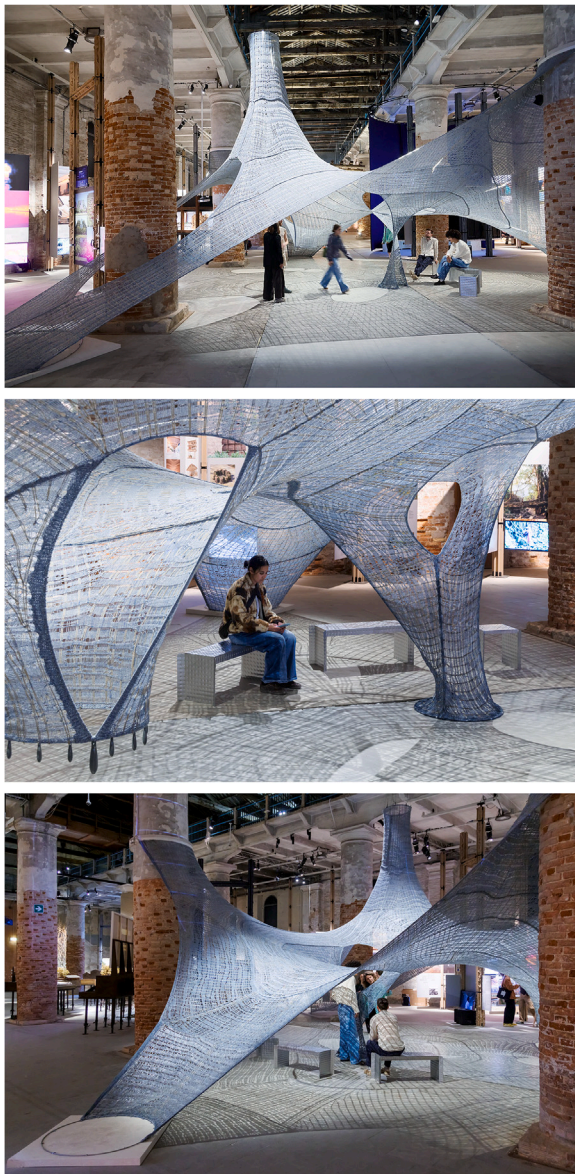


Fig. 12. Necto demonstrator at the Biennale d'Architettura, Venice, top: completed structure, center: close up of the internal opening and drilled ground support, bottom: close up of the column supports and stone plate ground support (photo credits: Iwan Baan).

more comprehensive experimental characterization will be required to establish a calibrated constitutive model suitable for predictive analysis.

A further limitation of the present workflow is that the FEA tool used in this paper is restricted to linear constitutive models and therefore cannot reproduce the nonlinear, anisotropic response described above. A more faithful representation of the hyper-elastic behavior of the knitted membrane would require a solver capable of handling such formulations.

Finally, the absence of experimental validation against the realized physical prototype. The predicted stress distributions, cable forces, and deformations obtained from the FEA have not been compared with in-situ measurements of forces, strains, or displacements in the built structure. Without such measurements, the accuracy of the computational predictions and the extent to which the simplifying assumptions, namely the discrete network representation, the isotropic membrane idealization, and the linear constitutive model, affect the structural response cannot be quantitatively assessed. Consequently, the numerical

results presented in this paper should be interpreted as design-stage estimates rather than validated predictions of the as-built behavior.

8.2. Future work

To enable a more accurate prediction of the textile membrane behavior beyond the discrete network approximation, future work will implement membrane-based finite element models capable of representing shear stiffness, stress redistribution, wrinkling phenomena, and cable-membrane slippage.

Future work will include a dedicated experimental characterization of the CNC-knitted textiles through biaxial tensile testing. The resulting data will be used to calibrate an orthotropic, hyper-elastic constitutive model and to establish reliable stiffness parameters for subsequent numerical analyses. To support this, the analysis framework will be migrated to an FEA environment capable of nonlinear, anisotropic material formulations, thereby enabling a more predictive assessment of the structural response under service and ultimate load conditions.

To address the absence of experimental validation of the computational workflow, future work will include the monitoring of the physical prototype through dedicated instrumentation. Load cells on the perimeter cables and support anchorages, strain gauges or fiber-optic sensors integrated into the knitted membrane will be considered. The acquired data will be used to evaluate the predictive capability of the proposed workflow, and to identify discrepancies between simulated and measured structural responses. Combining short-term load tests with longer-term monitoring would additionally enable the assessment of time-dependent effects such as creep and prestress relaxation, which are particularly relevant for bio-based textile membranes.

Future studies will explore a structurally driven hierarchical form-finding workflow. In this framework, Combinatorial Equilibrium Modeling (CEM) [12,51] will be employed at the conceptual stage to explicitly design and control the global force paths of the structure. Subsequently, a refined discretization that represents the underlying knitting pattern will be introduced, enabling a more detailed form-finding process using the Force Density Method (FDM) [10].

In parallel, future work will investigate optimization-based extensions of the FDM step, in which the force densities and, where appropriate, the network connectivity are derived from explicit structural objectives rather than tuned manually to reproduce a target shape. Approaches that couple the FDM with mathematical programming, such as the optimization framework for branching structures on free-form surfaces [52,53], offer a promising direction for systematically determining the structural topology and prestress distribution of bespoke knitted membranes. Integrating such formulations into the present workflow would reduce reliance on heuristic parameter tuning and improve the structural rationality of the equilibrium geometry passed on to the high-fidelity analysis.

Finally, from a computational standpoint, the workflow relies on a sequence of loosely coupled tools and software. While this modular structure offers flexibility, it introduces multiple data interfaces and limits closed-loop iteration across design stages. Tighter integration between geometric design, form-finding, and high-fidelity analysis would improve efficiency and robustness.

9. Conclusion

This paper presents the structural design, engineering, and detailing of *Necto* (Fig. 12), a full-scale CNC-knitted tensile membrane installed within the historically sensitive context of the Arsenale Corderie in Venice, Italy. The project adopts a multi-fidelity structural design workflow that demonstrates how geometric exploration, structural form-finding, nonlinear structural analysis, and detailing can be integrated into a coherent and robust design process.

By combining force density-based form finding with finite element analysis, the approach enables informed optimization of the global

geometry while maintaining consistency between design intent and structural behavior.

Beyond validating structural performance, the analyses conducted in this project actively shape the realization and use of the structure. A force-informed detailing strategy links form-finding results to detailed design, while structural assessment also defines operational constraints and safe modes of use for the structure. In this way, structural analysis becomes an integral design driver, demonstrating its expanded role in the conception and deployment of textile-based architectural systems.

The final built structure not only validates the underlying design methodology but also illustrates the potential of digitally fabricated textile architectures to engage sensitively with historic environments while achieving precise structural and spatial performance. At the same time, the combination of a form-active structural system and bio-based flax fibers highlights the potential of CNC-knitted membranes as low-embodied-carbon architectural systems.

CRediT authorship contribution statement

Anass Kariouh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Valentin Lorenzen da Silva:** Writing – review & editing, Validation, Software, Investigation, Conceptualization. **Nikoletta Christidi:** Writing – review & editing, Investigation. **Niclas Brandt:** Writing – review & editing, Investigation. **Mariana Popescu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Pierluigi D'Acunto:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve the grammar and readability of the text. After using these services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research presented in this paper is supported by the [European Union through the HORIZON–EIC Pathfinder Challenges programme under the FlexiForm project](#) (Project ID: 101162376; Call: HORIZON-EIC-2023-PATHFINDERCHALLENGES-0). The authors would like to thank Francesco Rinaudo and Sebastian Dietrich for their valuable engineering discussions. The authors also wish to acknowledge the Venice Biennale team for providing us the opportunity and supporting us in the realization of Necto.

Full credits Necto project

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SO–IL: Florian Idenburg, Jing Liu, Marlena Fauer, Demetri Lampris; Tailored Materiality Research (TU Delft / incoming MIT): Mariana Popescu, Niclas Brandt

Membrane design and engineering

Tailored Materiality Research (TU Delft / incoming MIT): Mariana Popescu, Valentin Lorenzen da Silva, Niclas Brandt, Nikoletta Christidi

Experience design

TheGreenEyl: Richard The, Noah Feehan, Ben Bojko, Saralee Sittigaroon, Arden Schager

Structural engineering

Professorship of Structural Design (TUM): Anass Kariouh, Pierluigi D'Acunto

Membrane fabrication and construction

Tailored Materiality Research (TU Delft / incoming MIT): Mariana Popescu, Nikoletta Christidi; Steiger Participation S.A.: Jean-Luc Lepieszko, Jean-François Cochez

Bio-coating and DNA data embedding, and error correction

Shaping Matter Lab (TU Delft): Kunal Masania, Jasper Groen; Functional Materials Laboratory (ETH Zurich): Robert Grass, Francesca Granito Professorship of Machine Learning (TUM): Reinhard Heckel, Maria Abu Sini

Sound design

Marian Mentrup

Assembly and construction

Mariana Popescu, Niclas Brandt, Valentin Lorenzen da Silva, Anass Kariouh, Nikoletta Christidi, Marlena Fauer, Richard The, Noah Feehan, Pierluigi D'Acunto, Jasper Groen Scenocracy s.r.l.: Mattia Menegotto, Fabio Pezzoni, Davide Alberti

Furniture

Tim Teven Studio

Opening performance

Riley Watts

Costume design

Elizabeth Beer

Supporters

Steiger Participation S.A.
Cornell University, College of Architecture, Art, and Planning
Jan Shrem and Maria Manetti Shrem Museum of Art, University of California, Davis
European Innovation Council (EIC) Pathfinder Challenge – FlexiForm & DiDAX
Creative Industries Fund NL
Consigli Construction Co., Inc.
TU Delft Climate Action Programme
Jakob AG

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