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# Shell and Spatial Structures

## Proceedings of IWSS 2023

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Stefano Gabriele · Amedeo Manuello Bertetto ·
Francesco Marmo · Andrea Micheletti
Editors

# Shell and Spatial Structures

## Proceedings of IWSS 2023

Springer

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# Preface

Shell and spatial structures represent highly efficient structural systems that blend optimized material utilization with effective structural forms. The ongoing advancement of analysis methods, design approaches, and construction techniques in this field has sparked growing interest among engineers, architects, and builders. The Italian Workshop on Shell and Spatial Structures (IWSS) focuses on a wide range of aspects related to shell and spatial structures. The second edition of the IWSS took place on June 26–28, 2023, at the Valentino Castle, an historic residence of the Royal House of Savoy and a UNESCO World Heritage Site since 1997.

The IWSS 2023 mascotte, the turtle *Shelly*, represents the feelings that the project of this workshop have brought to the organizers. In the collective imagination, the turtle is one of the most beloved animals, present in culture and myth, not only of western civilizations, but also in legends of Chinese, Indian, among Native Americans, and Pacific peoples. She is generally depicted as the one who holds up the world. Shelly thus gathers many meanings. Certainly, the appeal to the concept of the shell. Our turtle houses a real grid shell on its back. Shelly's accompanying motto *Shell we shape* is like a wordplay that invites participants to always find new ways for study and research without ever feeling stuck and never give up. In the myth, turtle is the point of contact and the boundary between sky and the Earth, between past and future and, in our case, it represents the undefined boundary between architecture and engineering, the limit between the beauty of a construction and whether it is really possible, buildable, realizable.

The IWSS 2023 represented an opportunity to comprehensive learning and sharing ideas, and participants had the chance to attend special keynote and plenary lectures of Italian and international speakers. Contributions were devoted to a broad range of topics related to experimental and theoretical studies, numerical methods and approaches for design, form finding, structural optimization, seismic analysis, sustainability analysis, stability analysis, manufacturing, testing, damage detection, structural health monitoring, maintenance, and historical reviews of all types of shell and spatial structures. The goal of the founders of the IWSS and chairmen of the 2023 event is to create a permanent network among researchers, professionals, and companies so as to make some structural engineering topics, which until now have been exclusively academic, closer to the world of work and business. This goal, in addition to making research topics current and usable, acts as a driving force for the development of new advances in science and research.

Participants to the IWSS 2023 had the opportunity to choose between two technical tours that demonstrate the legacy and the new perspective of shell and spatial structures. The first one, entitled *The Legacy of the Past*, consisted in a visit to Torino Esposizioni (Turin Exhibition Center) and Palazzo del Lavoro. The Turin Exhibition Center was conceived in the years immediately following World War II as a public exhibition space to host primarily the annual automobile show. The center houses some iconic concrete shell structures by Pier Luigi Nervi and Riccardo Morandi. They consist in three grand exhibition pavilions perfectly representing the structural art of these famous protagonists of contemporary engineering and architecture. The second tour, by the title of *The New Perspective*, allowed participants to visit the IAM@PoliTo, a mission-driven effort aimed at creating a comprehensive and multidisciplinary research platform for additive manufacturing. The overarching goal of this platform is to tackle the existing open challenges in the field of additive manufacturing, specifically in terms of machines, materials, and applications.

As part of the workshop, a permanent outdoor expo was held for the duration of the event, which featured the construction of two demonstrative structures: the Wings Pavilion and the Nested Tensegrity Balloons (Fig. 1). Both structures provided a valuable opportunity for joint work between research groups, faculties, researchers, and students. The first structure resulted from the collaboration between the groups of Giuseppe Fallacara and Amedeo Manuello, and it consisted of a saddle-shaped construction made from three arched structures built on the catenary principle and realized by steel chains and elastic cords. The second structure was designed by Andrea Micheletti and coworkers, in collaboration with the company Progetto Legno for the realization with modular wooden struts and marine ropes. The structural concept iterates the endoskeletal analogy of tensegrity systems by Kenneth Snelson, also known as the balloon analogy by Richard Buckminster Fuller, for which a stable tensegrity structure has the struts placed inside an outer network of cables. In this two-layer structure, two tensegrity balloons are placed one inside the other.

The IWSS 2023 collected more than 100 contributions which have been presented during the three days of conference, arranged into three parallel sessions and organized according to 14 main themes:

- *Form finding and optimization of shell and spatial structures*, organized by A. Manuello Bertetto, G. C. Marano and N. Lagaros
- *Multiscale structures for additive manufacturing*, organized by M. Galati
- *Structural theories and morphology: analyses and computational methods*, organized by A. Manuello Bertetto and J. Melchiorre
- *Historical vaulted structures: geometries and geometrical variations over time*, organized by C. Calderini and E. Piccoli
- *Analytical and numerical analysis of arches and vaults*, organized by S. Sessa and F. Marmo
- *Perspectives and advancements in construction of complex structures*, organized by S. Gabriele and A. Micheletti
- *Dynamics and stability of curved structures*, organized by A. Luongo
- *Space architecture: a multidisciplinary form finding*, organized by V. Sumini and M. Rossi
- *Monumental buildings and historical case studies: retrofitting and restoration*, organized by E. Lenticchia
- *Optimization in the analysis and design of shell and spatial structures*, organized by S. Gabriele and R. Cucuzza
- *Textile-hybrid structures, organized by A. Zanelli*, *Environmental impacts of shells and spatial structures*, organized by O. Iuorio
- *Realizations and case studies*, organized by G. Boller

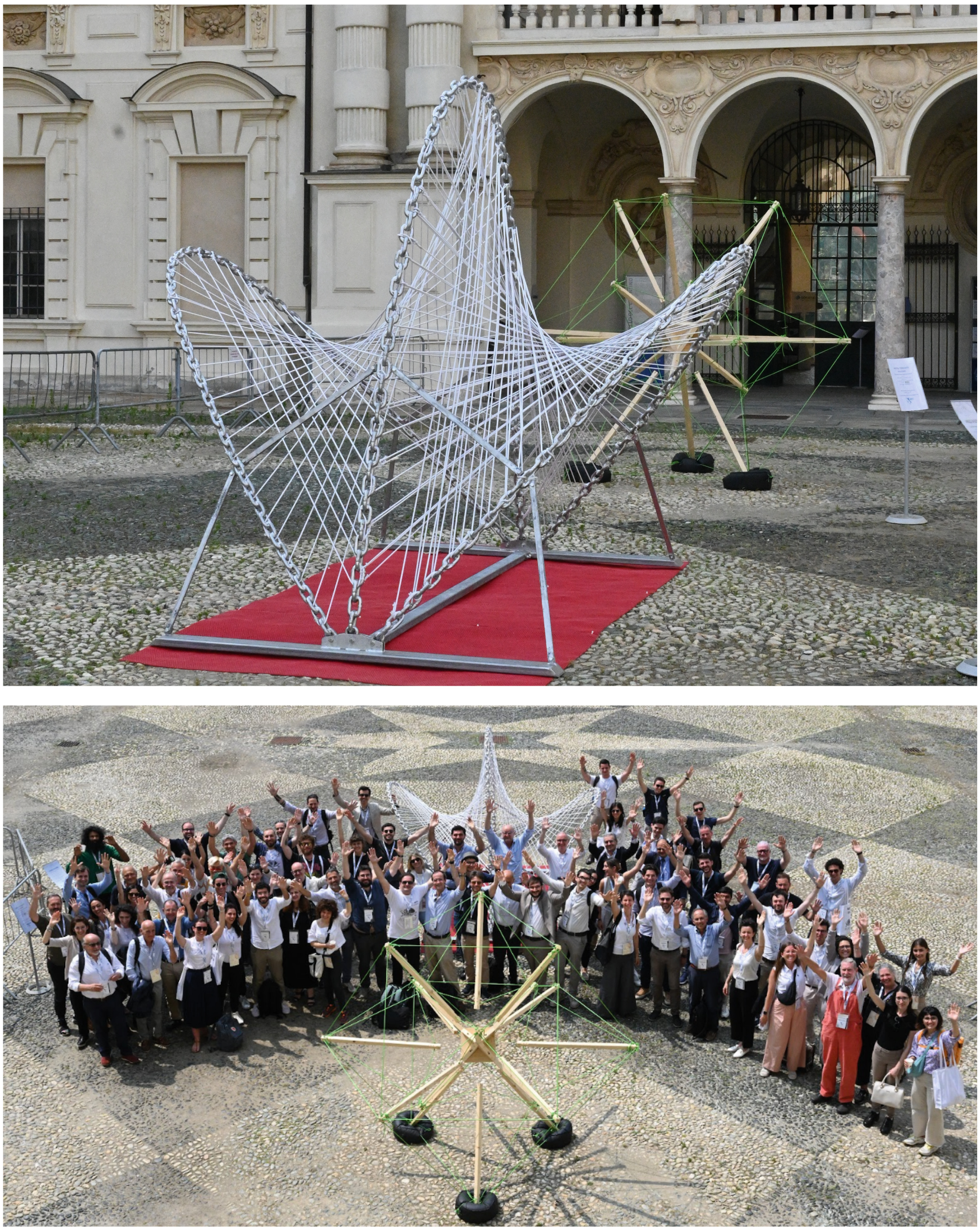

**Fig. 1.** Wings Pavilion and Nested Tensegrity Balloons (top). Participants group photo (bottom).

– *Stability of dome structures and space frames*, organized by A. Manuello Bertetto and F. Bazzucchi

The parallel sessions of all days of conference were introduced by plenary lectures of prominent experts in the field of shell and spatial structures. The plenary lectures of the first day are entitled *Understanding Tensegrity with an Energy Function*, given by Simon Guest, and *Form Finding by Shape Optimization with Implicit Splines and*

*Vertex Morphing*, given by Kai-Uwe Bletzinger. During the second day, Valentina Sumini gave the lecture entitled *Space Architecture: A multidisciplinary form finding*, and Hugo Corres Peiretti gave the lecture entitled *Relationship between the past and the present of shells and spatial structures. From the teachings of Eduardo Torroja to more recent achievements.* Sigrid Adriaenssens connected online from Princeton to give the lecture entitled *How shell we build now?*, a title that also inspired the motto of the IWSS 2023. The contributions of the last day were introduced by the plenary lectures by Carlos Lázaro, entitled *Two lightweight structures with steel-fiber reinforced concrete*, and by Charis Gantes, entitled *Structural Challenges Encountered in the Design of Tubular Steel Wind Turbine Towers.*

Parallel sessions were introduced by keynote lectures regarding specific aspects of the design, analysis and construction of shell and spatial structures. Specifically, Fernando Fraternali gave the lecture entitled *Designing seismic isolators through lattice metamaterials*, Maurizio Angelillo discussed about *Membrane Equilibrium Analysis for the assessment of traditional masonry structures and the design of new sustainable structures*, Giuseppe Fallacara presented the *New frontiers of stereotomic stone architecture*, Angelo Luongo's lecture regarded *Perturbation methods for nonlinear continuous systems: statics, buckling, resonances and dynamic bifurcations*, Massimo Cuomo talked about *Variational formulations for the form finding of flexible structures*, and Gabriele Milani presented *Two novel lower and upper bound 3D distinct element limit analysis models for masonry domes and vaults.*

The IWSS also hosted the Pier Luigi Nervi Prize, in order to recognize talented young researchers, designers, and engineers working in the field of shell and/or spatial structures. The Nervi Prize Commission examined more than 50 submissions to the IWSS 2023 authored by young researchers and decided to assign the Pier Luigi Nervi Prize to Francesco Laccone from the Institute of Information Science and Technology "Alessandro Faedo" ISTI of the National Research Council of Italy (in Pisa) for the work entitled *Static- and fabrication-aware segmented concrete shells made of post-tensioned precast flat tiles.*

Due to the high number of participants and the high quality of presented contributions, the Nervi prize Commission also assigned six ex-aequo mentions of honor to (in alphabetic order) Gloria Rita Argento, for the work entitles *Isogeometric refinement for shape optimization with a tunable number of variables*, Fabio Bazzucchi for presenting *Snap n roll tuning and listening to the progressive buckling of reticulated ensembles*, Romane Boutillier for the contribution regarding *Topology generation of architectural meshes adapted to the support conditions*, Claudia Chianese, who presented *Form finding of membrane shells via isogeometric analysis*, Marta Lembo who talked about *Nervi's isostatic lines inspired floor slabs. Beyond the archetypal Gatti Woolen Mill in Rome*, and to Jonathan Melchiorre, who showed *Gridshell Multi-step Structural Optimization with Improved Multi-body Rope Approach and multi-objective genetic algorithm.*

In this book of proceedings, we are going to present the contributions to the workshop in the form of short papers illustrating the topics discussed during the IWSS 2023. To give higher prominence to the Nervi Prize recognition, we first report awarded contributions, while all others are included in order of submission.

The organizers of the IWSS 2023 wish to thank the institutions that supported the IWSS 2023, such as Regione Piemonte and the Ordine degli Ingegneri della Provincia di Torino. In addition, the workshop was endorsed by the Società Italiana di Scienza delle Costruzioni (SISCo - Italian Society of Solids and Structural Mechanics) and by the International Association of Shells and Spatial Structures (IASS). Finally, the financial contributions received from the IWSS 2023 sponsors listed below are gratefully acknowledged.

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# Exploring the Potential of Fibrous Tectonics for Facade Application: A Form-Finding, FEM Analysis, and Optimization study

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**Abstract.** Fiber-reinforced polymer composites have garnered considerable interest in the field of structural engineering due to their promising mechanical properties. However, their application at the building scale still requires further efficiency. Current design approaches often rely on traditional methods used for conventional structural elements; in contrast, this paper focuses on the concept of fibrous tectonics. While thermoset matrices are commonly employed in this composite, our study focuses on developing a comprehensive computational workflow encompassing design, structural analysis, and optimization specifically tailored for fiber-reinforced thermoplastic polymer composite roving in facade applications. The primary objective is to minimize the length of the fiber roving used while ensuring acceptable levels of utilization and deflection, in addition to proposing possible architectural functions for using FRP at building scale, e.g., shading façades.

**Keywords:** Fiber-reinforced thermoplastic polymer composite · Finite-element analysis · Multi-objective optimization · Structural element · Geometrical form-finding · Fibrous construction

## 1 Introduction

Fiber-reinforced polymer (FRP) composites are composed of a polymer matrix embedding a fiber reinforcement, which can be a thermoplastic, elastomer, or thermoset material (Bhargava 2004). FRP composites possess notable characteristics such as high strength, lightweight, excellent fatigue resistance, a high elastic modulus, low thermal expansion, and corrosion resistance (Liu et al. 2015). Additionally, they exhibit anisotropic behavior, meaning they demonstrate varying properties in different directions (Waimer et al. 2013). Considering their composition, which consists of approximately 60% fiber reinforcement and 40% polymer matrix (Liu et al. 2015; Bhargava 2004), the mechanical properties of FRP primarily depend on the fiber direction, resulting in relatively high strength and modulus, while in the direction perpendicular to the fiber axis, the properties are influenced by the polymer and resin, leading to relatively lower strength and modulus (Liu et al. 2015). Also, they have some disadvantages like poor performance at high temperatures and expensive material and manufacturing costs (Viscuso et al. 2023).


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Although FRP composites have been used since the 1930s, they are now gaining popularity in the construction and structural industries (Bakis et al. 2002). They find applications in various industries in place of metal, including construction, military, energy, transportation, chemical, and electric power (Xue et al. 2022). FRPs can be used as structural elements, bridge decks, internal or external reinforcements for concrete structures, and for repair, strengthening, and pre-fabricated shapes (Bakis et al. 2002). However, there is still a need to optimize their design and fabrication processes for use on a building scale, as they have been successfully used in the aerospace and automotive industries (Waimer et al. 2013).

Despite the introduction of FRP as a novel material, traditional architectural and civil engineering design approaches rooted in conventional materials like wood, concrete, and steel continue to dominate architectural practices (Moskaleva et al. 2021). Achim Menges and Jan Knippers present an innovative biomimetic design approach in "Fibrous Tectonics" (2015) that was inspired by fibrous structures, which are found in most load-bearing natural systems. This paper also considers the use of FRP roving, considering the concept of fibrous tectonics, as a load-bearing structural element to create more efficient and sustainable structures, considering the unique properties and behavior of tailor-made continuous composites.

## 2 Research Aims and Methodology

Considering the costs, the traditional way of using FRP, and the lack of methodology to functionally use them in the building sector, this paper aims to present a computational workflow for the design, analysis, and optimization of fibrous construction as a facade structure. The investigation focused on the anisotropic behavior of tailor-made fibrous construction, which requires a different methodology compared to mesh-based orthotropic structures presented by Viscuso et al. (2023). The research project and investigation criteria can be summarized in the following list:

(i) A uniaxial lab test to determine the mechanical properties of the FRP;
(ii) Form-finding process and random fibrous pattern generation;
(iii) FEA analysis of the generated pattern to calculate the utilization by Karamba3D;
(iv) Multi-objective optimization for finding the best results based on equilibrium between material usage and structural efficiency;

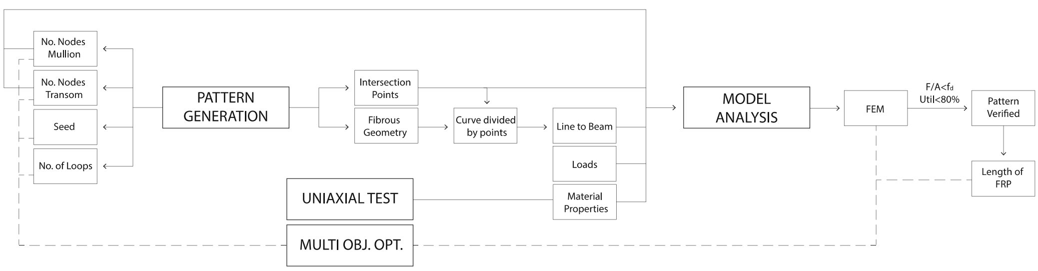


**Fig. 1.** Research overview

## 3 Uniaxial Lab Test of FRP Roving

The aim of a uniaxial lab test is to determine the mechanical properties of FRP roving, which refers to a bundle of straight strands wound onto spools. While thermoset resins are commonly used in fiber-reinforced polymer composites, this study focuses on a transparent elastomer thermoplastic resin. In this research project, the mechanical test was conducted on six specimens of pre-impregnated fiber-reinforced thermoplastic polymer composite with a 1200 TEX. The specimens had a cross-section area of 3.5 x 0.4 mm and a density of 2.5 g/cm$^3$.

The test involved applying a controlled load in a single direction to the glass fiber-reinforced thermoplastic polymer (GFRTP) composite sample until it reached the point of failure, allowing for the measurement of its breaking strain. The test procedure followed the guidelines outlined in Standard UNI ISO EN 1421:2017 and ISO 4606:1995. To ensure consistency, an initial strain of 10 N and a test speed of 100 mm/min were set for the experiment, as suggested by Besnard et al. (2006). The obtained test results provide crucial information about the linear anisotropic mechanical properties of the material, including tensile strength, elastic modulus, and other relevant parameters. These properties play a vital role in the design and analysis of the material for various structural applications, such as beams. Figure 2. Shows the uniaxial test on GFRTP samples.

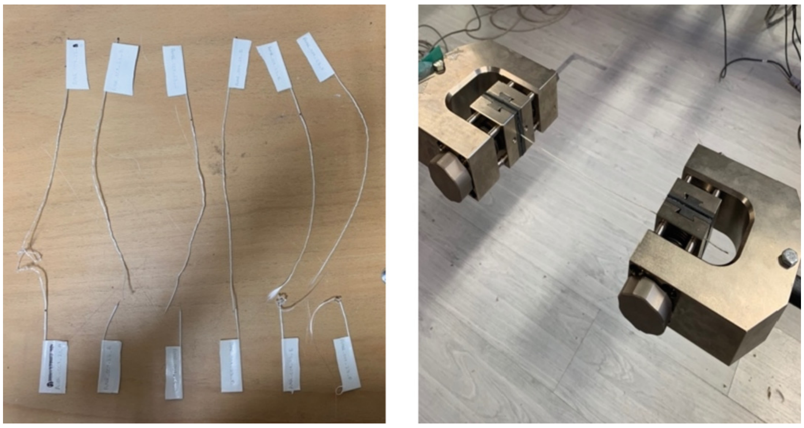

**Fig. 2.** Uniaxial Lab test of FRP roving done by TEXTILESHUB laboratory of POLIMI

## 4 Fibrous Pattern Generation

In this research, a random pattern generation approach is employed during the form-finding and optimization workflow for fibrous structures. The objective is to create a data set of possible design solutions by systematically testing different parameters. The random pattern generation is implemented using Grasshopper, a visual programming language integrated with Rhinoceros 3D. The authors have developed a custom code within GhPython for this purpose. The process begins with the existing frame serving as the base for the fibrous structure. The frame is divided into consecutive segments consisting of two mullions and two transoms. The number of nodes on each mullion and transom is determined by the input parameters X and Y. These nodes act as support points for the fibrous structure and are strategically placed on both mullions and transoms to facilitate the FRTP winding process. Certain constraints are applied to ensure the workability of the fibrous pattern; for instance, consecutive points cannot reside on the same mullion or transom.

The nodes within each segment are organized into four separate lists, each with distinct indexes. In each iteration of the fibrous structure, the code generates four random numbers within the range of 0 to (X and Y inputs minus 1), one for each list. These random numbers represent the index of the selected node from each list. By connecting these four selected nodes together, a loop of fibrous structure is formed. Each loop is represented as a closed polyline, resulting from connecting the four lines. To illustrate the concept, Fig. 3 provides a simplified depiction of the code generating one loop of the fibrous facade pattern.

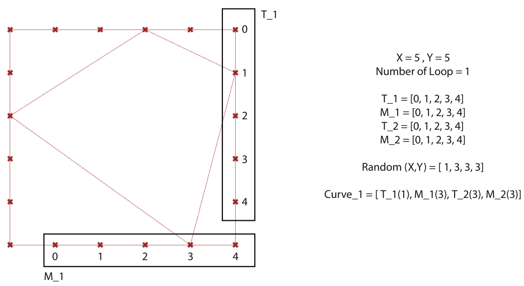


**Fig. 3.** Random Pattern Generation concept

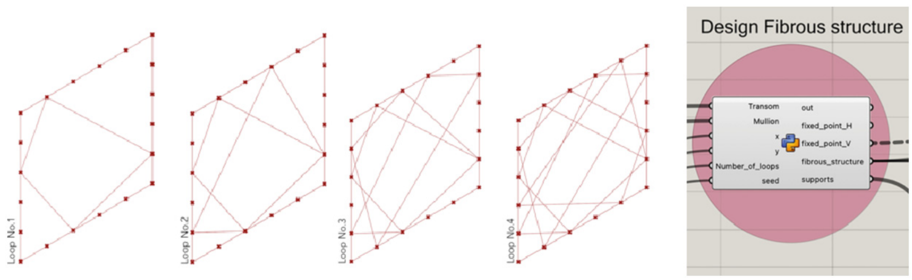


**Fig. 4.** Loop Generations and scripted code for generation fibrous pattern

Figure 4 illustrates the inputs and outputs of the scripted component used for random fibrous pattern generation. The 'seed' input serves as a pseudorandom number generator, influencing the generation of the pattern. On the other hand, the 'number_of_loops' input determines the quantity of loops involved in generating the fibrous pattern.

The outputs of the component are the supporting points and the fibrous structure itself. Both outputs play essential roles in the subsequent structural analysis. The values of the inputs, including 'X,' 'Y,' 'Number_of_loops,' and 'seed,' are variables that can be modified to produce different results. By adjusting these input values, a new fibrous pattern with distinct characteristics can be generated, enabling exploration and evaluation of various design possibilities.

## 5 Finite-Element Modeling (FEM) Analysis

The results obtained from the uniaxial mechanical test served as the basis for conducting finite-element modeling (FEM) simulations using Rhinoceros software. The previously generated fibrous patterns can now undergo structural analysis, taking into account the applied loads and assigned mechanical properties. The FEM analysis is conducted using the Karamba plugin for Grasshopper, an interactive and parametric finite element program (Preisinger et al. 2014). To analyze the behavior of FRTP roving in Karamba 3D, the first crucial step is to determine the appropriate structural element type for simulation. One of the key questions is whether the FRTP roving should be modeled as a beam, truss, or cable element. Once the choice is verified, the analysis process can proceed by following the typical steps of assembly, analysis, and result interpretation. These steps involve defining the structural components, applying loads and boundary conditions, performing the finite element analysis, and examining the obtained results.

### 5.1 Selection of Structural Element Type for FRTP Roving

In the context of finite-element analysis, beam elements are utilized as one-dimensional finite elements oriented in three-dimensional space. These elements require a minimum of two nodes placed at their ends to define their geometric properties. Beam elements are particularly well-suited for representing structural elements where one dimension dominates over the other two. In the case of FRTP roving, while it can be initially defined as a beam, it exhibits a bending moment of zero. This characteristic aligns more closely with the behavior of a 'truss' structural element. Truss members are assumed to be connected by idealized pin joints that permit rotational movement while restricting translation. The pin joints enable trusses to primarily bear axial loads, either in tension or compression, along their members. For FRTP, the presence of pre-tensioning must also be considered. Consequently, FRTP roving can be regarded as a pre-tensioned truss structural element or simply as a cable.

To validate this condition, a FRTP roving structural element with a length of 5 m and a cross-sectional area of 0.056 cm is analyzed. The analysis accounts for a point load of 1 kN applied at the element's center and two fixed translation supports at its ends. Manual calculations suggest a maximum displacement of approximately 91 (Fig. 5–3); however, the finite-element analysis yields different results. When considering the FRTP roving structural element as a continuous element, the calculated maximum displacement is zero (Fig. 5–1), indicating an incorrect calculation. To address this discrepancy, the FRTP roving structural element is divided into smaller elements (in this case, five pieces), which are connected by fixed translation joints (Fig. 5–2). The obtained result aligns with the manual calculation, confirming the accuracy of the simulation and the suitability of the truss structural element type for FRTP roving.

The results of the finite-element analysis (FEA) have been obtained using the Karamba 3D algorithm based on second-order theory. In this analysis, the displacements are directly related to linear deformations and tensions within the structural elements. By employing this approach, a more accurate representation of the behavior of the FRTP roving can be achieved.

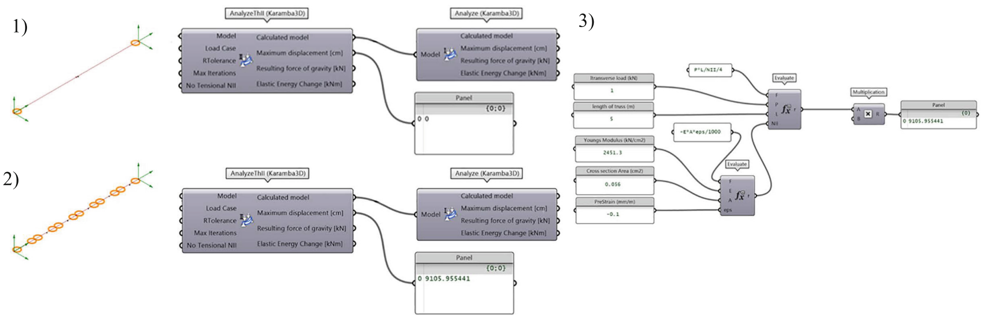


**Fig. 5.** Verification of Structural Element Type for FRTP Roving

## 5.2 Analysis Process: Assembly, Analysis, and Result Interpretation

During the assembly stage, several components such as "LineToBeam," "Support," "Load," "MaterialProperties," and "Cross-Section" are utilized to feed the "AssembleModel" component. The polylines obtained from the pattern generation result are connected to the "LineToBeam" component to define the geometry and shape of the fibrous structure. The nodes generated in the pattern generation process are designated as "supports" with zero degrees of freedom in translation (to represent the pin joints). The "load" component incorporates various load conditions. The initial strain is defined to account for the pre-tensioning of the fibrous beams. The wind load is calculated based on EN 1991 wind action on buildings for Milano, Italy, and is applied as a linear distributed mesh load. Additionally, the effect of gravity is considered by applying a "gravity" load. The "temperature load" is also taken into account as a relevant load condition. The inputs for the "MaterialProperties" component are determined based on the results of the uniaxial mechanical test. While FRTP roving behaves as an isotropic material, it is important to note that FRP itself is an anisotropic material. The cross-section is simplified as a filled trapezoidal section with a height of 0.04 cm and a width of 0.35 cm for a single layer of FRTP roving. The number of roving layers can influence the height of the section, which affects the moment of inertia and maximum deflection of the beam. In the final step, all these components are connected to the "AssembleModel" component, which collects the necessary data and initiates the analysis process.

Finally, the model is ready to be analyzed using the 'AnalyzeThII' component, which employs second-order theory. This component calculates the maximum vertical displacement in the fibrous structure, a critical parameter for verifying its performance. According to the EN-14351-1 standard, the deflection limit under wind load should not exceed the length divided by 200 or 15 mm. This criterion is a benchmark to assess the maximum vertical displacement obtained in the analysis. The 'ReactionForce' and

'BeamForce' components provide valuable data on reactions and internal forces, respectively. The reaction forces are instrumental in designing the structural nodes, while the axial forces enable accurate dimensioning of the FRTP roving.

The 'utilization' component offers insights into the relationship between stresses and the section's strength capacity. If the output value exceeds unity, it indicates that the section has surpassed its yield tension. In this research, a conservative maximum utilization of 80% is considered to ensure the appropriate utilization of the structural elements (Fig. 6).

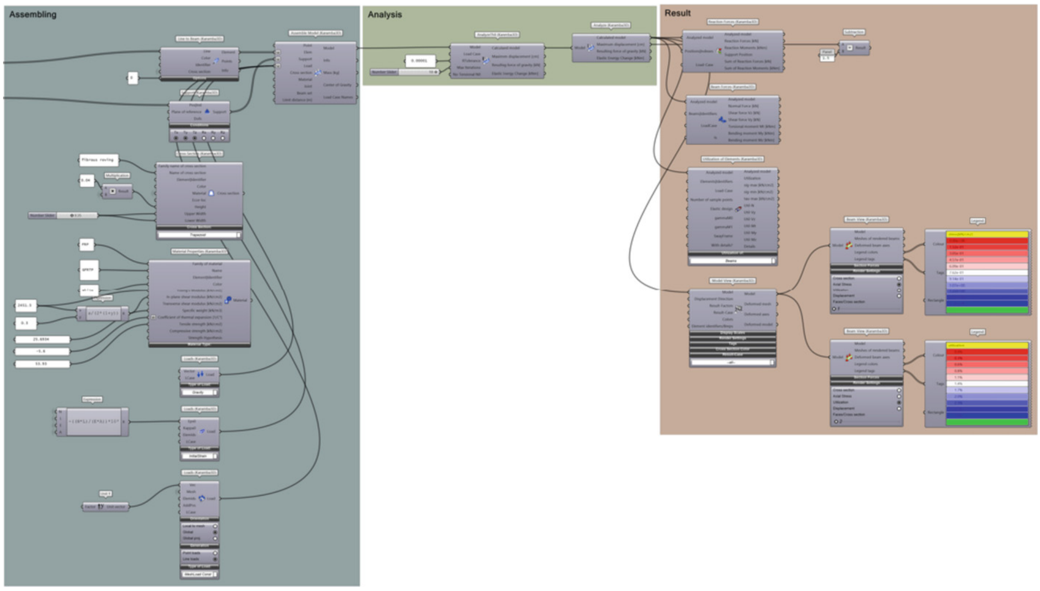


**Fig. 6.** Loop Generations and scripted code for generation fibrous pattern

## 6 Multi-objective Optimization (MOO)

The combination of random fibrous pattern generation and FEM using Karamba 3D offers the opportunity to employ multi-objective optimization (MOO). In the field of computer-aided architectural design (CAAD), the form-finding process has evolved beyond a single objective of structural form-finding. Designers are now guided by multiple objectives to achieve the best or near-best results (Brown 2016). The MOO process (Gunantara 2018) enables the identification of optimal fibrous patterns that are structurally verified and possess the minimum possible length. Table 1 and Table 2 present the variables and objectives involved in the optimization process. To perform multi-objective optimization, the research utilizes Wallacei, a plugin for Grasshopper developed by Makki et al. (2019). Wallacei incorporates the NSGA-2 (Non-dominated Sorting Genetic) algorithm (Deb et al. 2000) as the primary evolutionary algorithm, empowering users to run comprehensive evolutionary simulations.

**Table 1.** Table of Design Space Variable

| Symbol | Variables | Font size and style |
|---|---|---|
| X1 | Number of anchor points on mullion | x > 5 |
| X2 | Number of anchor points on transom | x > 5 |
| X3 | Number of loops | 1 < x < 20 (Assumption) |
| X4 | Random Selection of anchor points (seed) | x > 1 |
| X5 | Number of FRTP roving layers | 1 < x < 5 (Assumption) |

**Table 2.** Table of Objective Function Assumptions

| Objectives | Metric (condition, unit) | Evaluation method |
|---|---|---|
| Max Deflection | Max deflection in model (= < 15, mm) | FEA |
| Max Utilization | Utilization of all active elements (< 80, %) | FEA |
| Structural Efficiency | FRP's length (min, m) | Geometric measurement |

## 7 Results and Visualization

After setting up the fibrous pattern generation, finite-element analysis, and defining the variables (genes) and objectives, the optimization process can be initiated. The search space consists of 3.1 x 10^6 potential results; however, for this study, the researchers selected a population size of 8000 individuals in 400 generations, with 20 individuals per generation. While the first generation was generated randomly, subsequent generations are produced through the mutation of the previous generation, introducing further variation and exploration. For result visualization, Fig. 7–1 presents a projection of all the results onto a 3D tri-objective plot, offering a comprehensive visual representation of the optimization outcomes. The Pareto front are indicated with yellow rectangles. Additionally, Fig. 7–2 displays parallel coordinate plots depicting each generation based on objectives. In the plots, earlier generations are represented by the red color, while the blue color represents the latest generations. Figure 8 showcases a catalog of results, featuring the 20 results from the Pareto front and an additional selection of 34 results chosen by the authors.

The final decision and selection of the optimal solution can be influenced by various factors, including the prioritization of design variables (Brown 2018), aesthetic considerations, ease of construction, or other measurable variables like the calculation of shading to enhance comfort within internal spaces. While the decision-making process is not extensively explored in this research, Fig. 9 provides an illustration of axial forces, utilization forces, and deflection for one of the potential solutions.

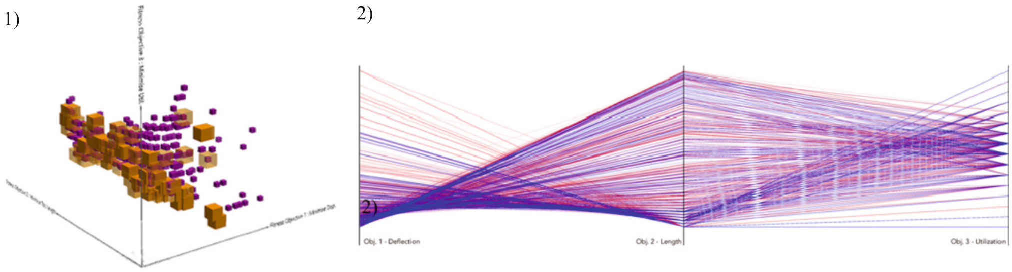


**Fig. 7.** Visualization of data on the tri-objective and parallel coordinate plots

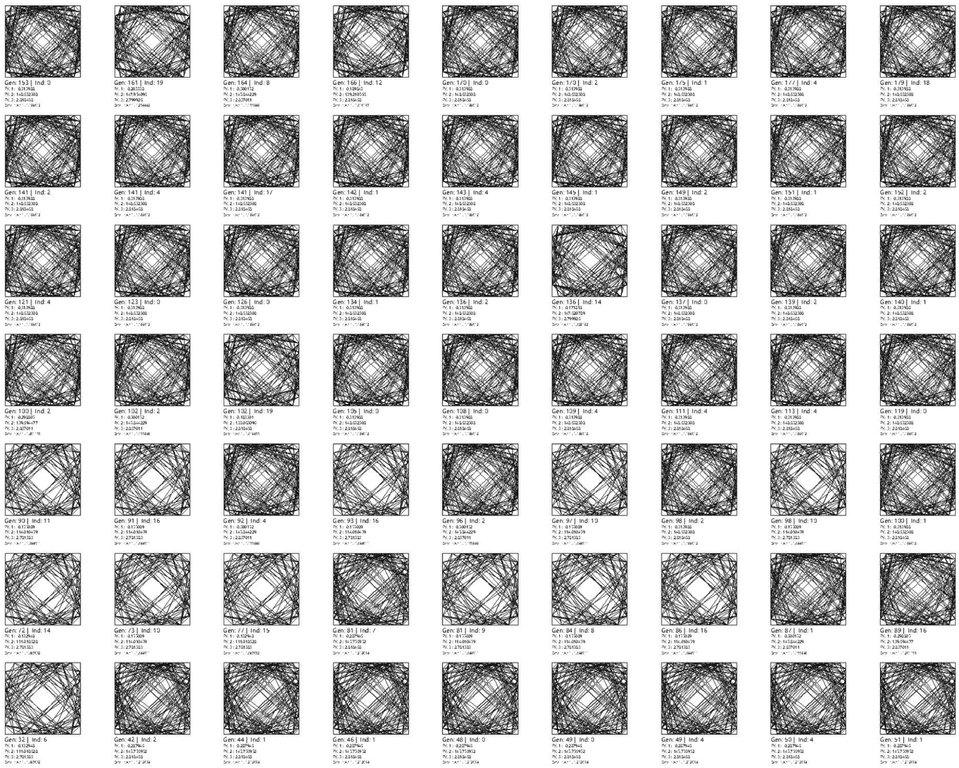

**Fig. 8.** Catalogue from design space sampling

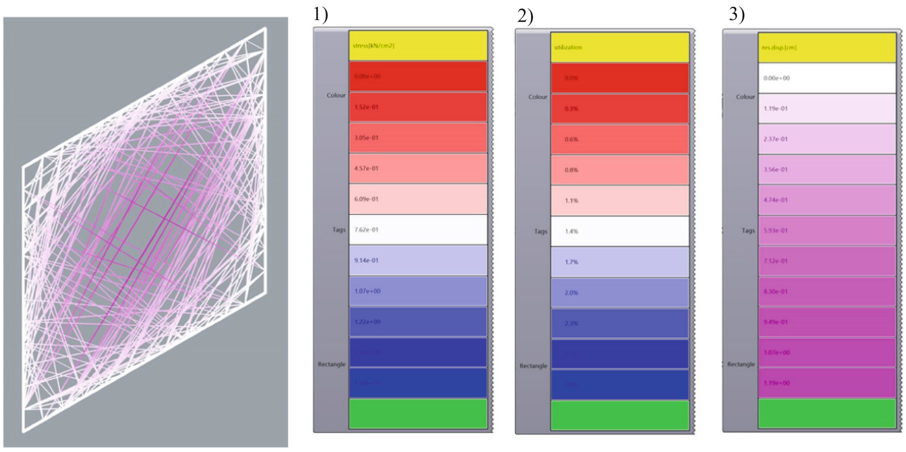


**Fig. 9.** FEA of one possible solution (1-Axial Stress, 2-Utilization, 3-Deflection)

## 8 Conclusion

This paper presents a methodology that integrates structural analysis into the architectural design environment for fibrous structures. The computational workflow enables designers to seamlessly design, analyze, simulate, and optimize their structures by exchanging data between Rhino Grasshopper, Karamba, and Wallacei. This integration offers benefits such as improved efficiency, enhanced design exploration, and informed decision-making. The interactive visualization of optimized solutions provides designers with a clear understanding of the structural verification process. This methodology has the potential to significantly advance the field of fibrous structures and transform the design process, allowing for more efficient and informed design decisions.

We would like to express our sincere gratitude to i-mesh company for providing the materials used in this research. Additionally, we extend our thanks to the TextilesHUB lab at POLIMI for conducting the uniaxial tests on the materials. Their expertise and assistance have greatly contributed to the success of this research.

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