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Design-to-Production Process for Large-Scale Inflated Tensegrity Artwork

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Abstract

Inflated steel elements are a controllable, yet highly expressive modelling technique. They are subject to buckling during the fabrication process, which gives structural strength when strategically controlled and allows to create unique manufacts such as tensegrity structures. As well as other mould-free methods, such as Incremental Sheet Forming (ISF), inflated steel elements do not require a formwork, highlighting their sustainable property. A minimal amount of material guarantees lightweight structural stiffness, leading to an efficient use of resources. Furthermore, previous studies have shown that they have structural properties amenable to large constructions.

In this paper, we describe the case study of an inflated steel tensegrity artwork by presenting its mechanical attributes and aesthetic qualities. To accommodate the inflated steel element configuration of interest, it is essential to predict the shape closest to the relaxed final stage through a digital model. We thus analyse relevant parameters such as deformation and local torsion to assure structural stability. In addition, the elements present a longitudinal double-sided crease, which allows to steer the buckling and enforces the structural properties of the element itself. A physical prototype is then fabricated with an air pressure-based method.

The workflow has been tested for the design, assembly and production of a permanent tensegrity artwork. The paper also provides details on the precise assembly of the thirteen uniquely shaped elements. The tensegrity principles employed contribute to the success of this innovative approach in large-scale inflated steel constructions.

Keywords: conceptual design, form finding, inflated steel, steered buckling, digital simulation, optimization, tensegrity structure.

1. Introduction

In recent years, the integration of art into urban landscapes has emerged as a pivotal aspect of city development projects, contributing to the aesthetic enrichment and cultural vibrancy of public spaces. The confluence of artistic expression and architectural innovation has paved the way for the conception of groundbreaking artworks that not only captivate audiences but also resonate with the historical and societal context of the surroundings. In this context, the competition announced by the Port Authority of the Eastern Ligurian Sea (ADSP) for the creation of an artwork to embellish the fountain in Largo Fiorillo, La Spezia, represents a significant opportunity to blend artistic ingenuity with the commemoration of a longstanding maritime tradition – the Palio del Golfo. The competition brief calls for the design and implementation of a distinctive artwork that pays homage to the Palio del Golfo, a boat race among the 13 villages of the ligurian gulf.

In response to this call, the present paper introduces a novel approach for large-scale artworks, through the design to production process within the field of tensegrity structures. *Tensegrity*, a term coined by David Georges Emmerich, Richard Buckminster Fuller and Kenneth Snelson (Motro [1]), refers to a structural system characterized by the use of isolated components under compression inside a network of continuous tension. This distinctive architectural paradigm offers a myriad of possibilities for creating visually captivating and structurally robust artworks that defy traditional notions of form and function.

By leveraging computational algorithms and simulation techniques, designers can explore diverse design iterations, optimize structural performance and streamline the fabrication process. This facilitates the realization of ambitious artworks that push the boundaries of artistic expression and engineering innovation. Focusing specifically on the integration of computational methods within the design and fabrication processes, we delineate a comprehensive framework to implement large-scale inflated tensegrity artworks. Overall, the paper elucidates the potential of digital technologies in realizing tensegrity structures at a scale suitable for urban installations. We believe that the artistic experimentation and urban renewal resonates with the spirit of the Palio del Golfo, in La Spezia.

2. State of the Art

The integration of tensegrity sculptures with inflated steel techniques marks a significant milestone in the realm of architectural innovation (Ayres et al. [2]). While both technologies have independently flourished over the years, their fusion into a singular, permanent artifact represents a pioneering endeavour. Tensegrity sculptures, rooted in the visionary work of artists like Buckminster Fuller and Kenneth Snelson, have long captivated audiences with their intricate balance of struts and cables. Similarly, inflated steel techniques leverage principles of air pressure and tensile strength, thus pushing the boundaries of architectural form and function. However, only recently the advancements in computational design tools, digital fabrication techniques, and structural engineering have allowed a seamless integration of tensegrity sculptures with inflated steel elements. This convergence not only presents an unprecedented opportunity for creative expression, but also holds promise for redefining the possibilities of structural design in the built environment.

2.1. Tensegrity Sculptures

Tensegrity sculptures represent an intriguing intersection of art, engineering, and mathematics, pushing the boundaries of what is possible in structural design. These sculptures consist of a network of struts and cables, where the struts are suspended in a state of tension by the cables, creating a captivating display of balance and self-stability.

Starting from the works of Buckminster Fuller and Kenneth Snelson in the mid-20th century, tensegrity structures have since evolved into a vibrant field of artistic exploration and architectural experimentation. Today, contemporary artists and designers continue to push the boundaries of tensegrity sculpture, exploring new forms, materials, and applications (Furuya et al. [3]). These sculptures not only captivate the viewer due to their innovative beauty but also inspire deeper reflections on the interconnection between art, science, and nature.

More recently, Tibert and Pellegrino studied different configurations in order to find one suitable for deployment to be used in space design, resulting in the creation of the 6T-Prism Structure Rotation from a hexagonal prism. Among these tensegrity applications, there have been many others, such as robotically controlled ones, larger ones for roof domes, or smaller ones with integrated membranes suitable for smaller pavilion arrangements. One tensegrity bridge worth mentioning is the Kurilpa Bridge, designed by Arup, Cox Rayner, and Baulderstone, and built in 2009 in Brisbane (Gomez-Jauregui et al. [4]).

2.2. Inflated Steel Technique

The state of the art in inflated steel elements represents a fascinating convergence of structural engineering, materials science, and architectural design. Inflated steel elements, utilize the principles of air pressure and tensile strength to create lightweight and dynamic architectural forms. These structures often feature a network of steel or metal frames inflated with pressurized air or liquids, resulting in visually striking shapes that appear to defy gravity (Rawlings [5]). Advancements in computer-aided design (CAD) have enabled designers to optimize the aerodynamic performance and structural integrity of inflated steel elements, allowing for greater complexity and innovation in their design (Ayres et al. [6]). Furthermore, advancements in fabrication techniques, such as laser cutting and robotic welding, have made it possible to customize the inflated steel elements with remarkable precision. As a result, inflated steel elements have found applications in a wide range of architectural contexts, from temporary pavilions to short-spanning balloon bridges (Zięta et al. [7]). The state of the art in inflated steel elements continues to evolve, offering new opportunities for creative expression and sustainable design in the built environment.

Among the artists pioneering this free form inflating technique, notable figures include Franz Bahr, who has been inflating steel since 1991, and Stephen Newby, proprietor of Full Blown Metals, renowned for his craftsmanship in producing bespoke inflated elements. Newby patented the Blown Metal™ technique in 2001, contributing significantly to our innovative approach to large-scale inflated steel construction. Additionally, Oskar Zięta has made significant contributions through his work on "Nawa", a permanent artwork crafted through Freie Innen Druck Umformung (internal pressure-forming) at CAAD, ETH Zurich. This project features 35 polished steel arches within an urban sculpture-pavilion on Daliowa Island in Warsaw, exemplifying the transformative potential of this technology (Zięta n.d. [8]).

3.0. Concept Idea

Our study presents a novel approach to architectural design through the integration of inflated steel elements above the existing fountain in Largo Fiorillo. The elements are 13 in order to represent the 13 neighboring villages that annually participate in the Palio del Golfo boat race [Figure 1].

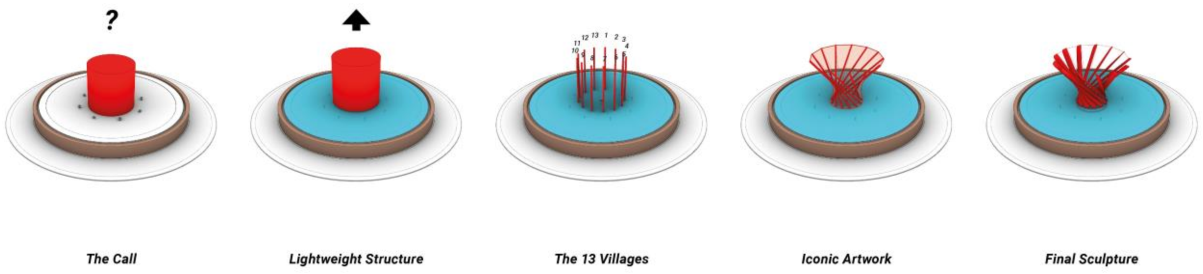


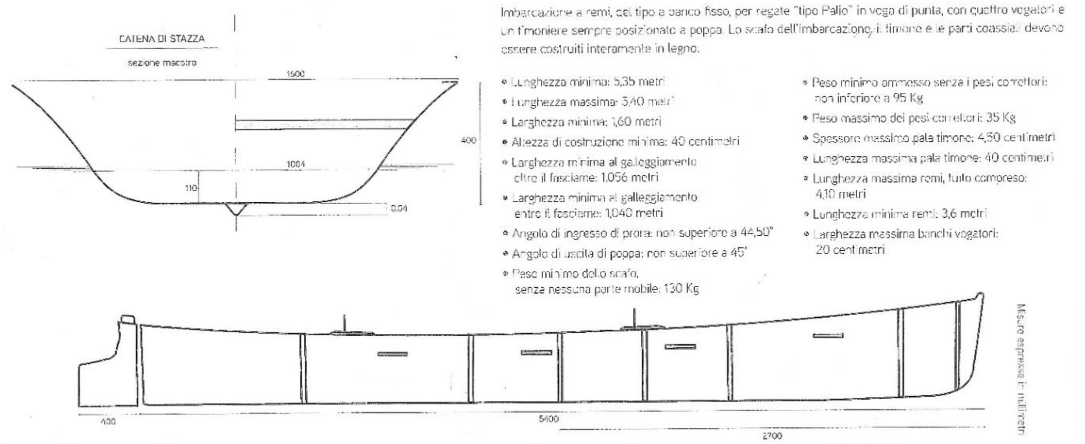
Figure 1: Development of the conceptual idea for the design competition.

The elements resemble the profile of the boats used in the race and their lightweight characteristic mirrors their gliding over the water. Furthermore, they are placed in a cylindrical tensegrity system to establish a direct communication with the profile of the Cathedral Cristo Re in Piazza Europa [Figure 2]. The harmonious dialogue between the two adjacent spaces represents a link between contemporary design and historical context. We have also oriented the elements to point towards the villages surrounding the gulf [Figure 3]. The synthesis of lightweight materials, structural design and symbolic integration exemplifies a progressive paradigm in architectural practice, bridging tradition with innovation in urban landscapes.

Figure 2: A) The final artwork, built in place in Largo Fiorillo. The hyperboloid outer silhouette matches the silhouette of the adjacent Cathedral Cristo Re in Piazza Europa [©Enrico Pontello] B): Element orientation arranged according to their local disposition of the villages in the gulf of La Spezia.

3.1. Element Shape

The design of the artwork's structural elements draws inspiration from the sectioned profile of the traditional boat employed in the Palio del Golfo [Figure 3]. By replicating the symmetric shape of this boat's section, the structural elements serve to symbolize the cultural significance and maritime heritage of the Palio del Golfo tradition. Moreover, each structural element is personalized with the name and boat number of the participating villages, making each piece unique and reflective of the local identity.



Imbarcazione a remi, del tipo a banco fisso, per regate "tipo Palio" in voga di punta, con quattro vogatori e un timoniere sempre posizionato a poppa. Lo scafo dell'imbarcazione, il timone e le parti coassiali devono essere costruiti interamente in legno.

- Lunghezza minima: 5,35 metri
- Lunghezza massima: 5,40 metri
- Larghezza minima: 1,60 metri
- Altezza di costruzione minima: 40 centimetri
- Larghezza minima al galleggiamento oltre il fasciame: 1,056 metri
- Larghezza minima al galleggiamento entro il fasciame: 1,040 metri
- Angolo di ingresso di prora: non superiore a 44,50°
- Angolo di uscita di poppa: non superiore a 45°
- Peso minimo dello scafo, senza nessuna parte mobile: 130 Kg
- Peso minimo ammesso senza i pesi correttori: non inferiore a 95 Kg
- Peso massimo dei pesi correttori: 35 Kg
- Spessore massimo pala timone: 4,50 centimetri
- Lunghezza massima pala timone: 40 centimetri
- Lunghezza massima remi, tutto compreso: 4,10 metri
- Lunghezza minima remi: 3,6 metri
- Larghezza massima banchi vogatori: 20 centimetri

Figure 3: Technical drawing of local racing boat, extracted from page 175 of *"AA.VV., Palio del Golfo della Spezia 1925-2015. Novant'anni di passione, Giunti Editore".*

The elongated shape of the inflated element reflects the longitudinal section of the boat, with filleted corners indicating the bow. Similarly, the cross section has been designed following the profile of the keel and mirrored symmetrically to create a closed and rigid element. To symbolize the counter-keel in the inflated steel element, we created a longitudinal crease defining the geometry along its entire length [Figure 4].

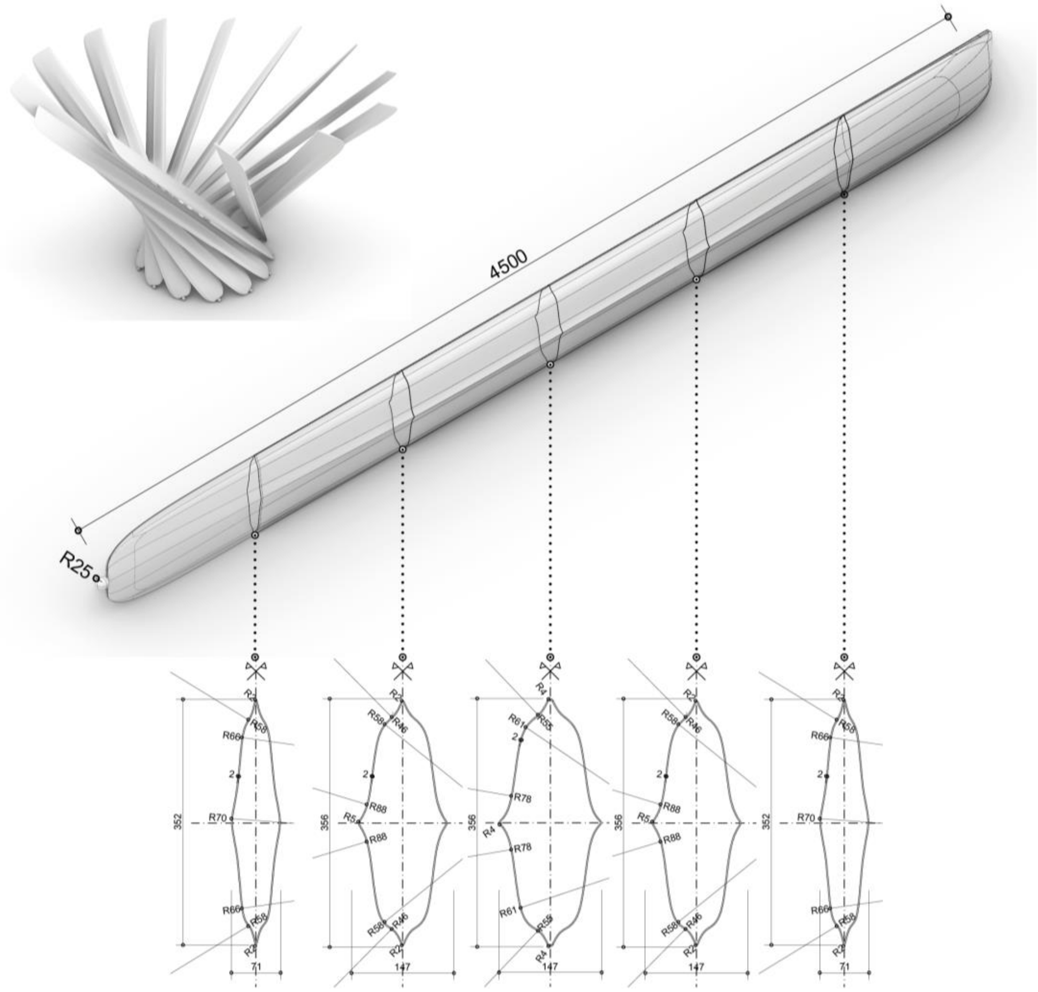


Figure 4: Radial arrangement of the 13 uniquely shaped inflated elements, perspective view of the single element and its progressive cross sections. All units of measurements are in millimeters and refer to the final pieces. The prototype is scaled 1:2.

4.0. Methods

The initial design concept for the whole tensegrity artwork served as the foundation upon which we iteratively refined and improved our fabrication details. Integral to this refinement process was the expertise contributed by Maco Technology, the fabricator specializing in advanced manufacturing techniques. Utilizing digital modelling tools, we analysed relevant parameters such as deformation and local torsion to ensure structural stability while maintaining our desired aesthetic appeal.

4.1. Element Fillet Optimization

This paragraph describes the practical steps taken to mitigate the steel weld wrinkles arising from sheet curvature (Neto et al. [9]). Inflated steel elements have been previously digitally simulated providing valuable insight into the behaviour of the free-form shapes under inflation (Metzger et al. [10]). The objective was to achieve a seamless G3 fillet continuity along the profile of each element while adhering as closely as possible to the conceptual boat-shaped reference [Figure 5]. To achieve this, the Evolutionary Algorithm called Galapagos in Grasshopper for Rhinoceros 3D was used. The design recreated the fillet setting within the Grasshopper framework, crafting a system comprising eight movable control points and a degree 7 single-span curve. These control points serve as our variable parameters dictating the fillet's characteristics. Galapagos, a plugin harnessing evolutionary principles within Rhinoceros 3D, enabled to leverage the inputs of Genome and Fitness to steer the exploration. Genome encapsulates the four parameters defining the fillet curve's genes, while Fitness minimizes the deviation between the new G3 fillet and the original curve across multiple sample points. During the iterations in Galapagos, several potential solutions are evaluated, the fittest curves survive and propagate their genetic components into subsequent generations. Resembling the essence of natural selection, suboptimal solutions are systematically pruned, paving the path towards convergence upon an optimal fillet curve (Agrawal n.d. [11]).

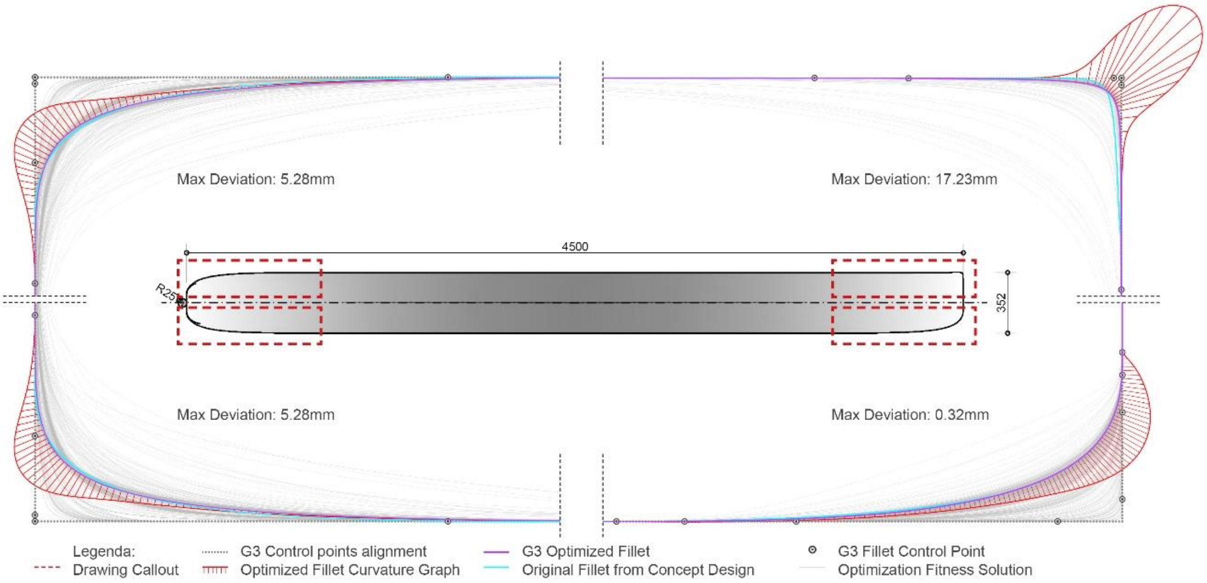


Figure 5: Fillet optimization for the inflated element shape corners.

4.2. Prototype development

Prior to producing the 13 uniquely shaped elements, a prototype at a 1:2 scale, utilizing a 0.9mm sheet, was crafted by Full Blown Metals. With the profile edges refined according to the optimized digital model, two A16 stainless steel sheets were cut to match the specified profiles. A pre-machining process was employed to create a longitudinal crease on each sheet. The crease, meant to symbolize the boat's counter-keel and enhance structural rigidity, is formed by a motorized bead roller [Figure 6A]. Thus, the steel sheet acquires an initial engraving before being welded and blown, which steers the buckling and reinforces the element's strength properties. The longitudinal crease enhances the structural rigidity in several ways. Firstly, it effectively increases the material's cross-sectional area and redistributes evenly the applied loads, thereby strengthening the structure against bending and torsional forces. Secondly, bead rolling alters the material's microstructure, aligning grains along the direction of deformation, which improves its resistance to plastic deformation and load-bearing capacity. Thus, the welded element becomes more resistant to deformation and capable of withstanding higher mechanical loads. The next step involved welding the edges of the sheets and seamlessly integrating a 20mm steel plate with its female connections. The element was then inflated with air to achieve its intended shape. It's important to note that the elements maintain internal pressure upon completion, which contributes to their structural integrity and final form. In the context of tensegrity structures, these elements can be treated as pure compression members. The internal pressure significantly increases the collapse strength compared to an uninflated element of the same geometry. This enhanced strength is due to the pre-stress induced by inflation, which helps resist buckling and increases the overall stability of the structure. To finalize the piece, a sandblasting process was employed using aluminium oxide. This method closely resembles bead blasting while also offering the benefit of being non-ferrous, thus preventing rusting and preserving the aesthetics of the sculpture [Figure 6A,B].

Figure 6: A) Bead-rolled crease and sandblasted text over the inflated prototype [©Joe Laws Photography]
B): The prototype in scale 1:2 of the inflated steel element [©Joe Laws Photography]

5.0. Structural Analysis

From the inception of the design process, Maco Technology has provided assistance in ensuring the structural stability of the sculpture and refining the steelwork connections between the elements. The analysis and considerations that have guaranteed the assembly of the artwork are presented below.

5.1. Element rotation

In the majority of tensegrity sculptures constructed over the past 40 years, the single elements were usually cylindrical and this required only a connection along the main axis for the forces to be exerted by the steel cables. In this particular artwork, the steel elements deviate from the uniformly cylindrical tubes. Instead, they feature the unique design reminiscent of racing boats, described in section 3.1. The literature from the nautical world provided the solution to address the challenges resulted from this configuration. By utilizing the bow of the boat as an anchoring point, the weight of the inflated element could be offset off-axis. This was achieved by employing two points of connection: at the top, one point to link all the inflated elements together with a horizontal steel cable, and at the bottom, a second point to connect the base of each element to the ring beam.

The connection at the top needs to offer rotational freedom, in order to accommodate the inflated element's rotation in three directions within space. Consequently, a 20mm angled plate was crafted to facilitate this connection, receiving the rotating rod holder with U-mound and effectively compensating for the other two angle rotations [Figure 7].

Figure 7: Upper node connection between the cables and the inflated steel element [©Enrico Pontello].

A similar solution to the top connection was adopted for the bottom connection. Placing the bottom connection in the middle of the base would have resulted in an eccentricity, with an arm half the width of the inflated element. Hence, the inflated element was treated as a "simplified rectangle" and the connection positioned at the opposite corner, effectively pinching it. However, this resulted in a local rotation of the element, which requires stabilization. To solve this, a double hole was created at the bottom of the element and then a rod was screwed to lean the entire inflated element on a second support inside a notched steel plate bolted underneath the ring beam.

To allow for some flexibility and drawing inspiration from the design of a boat's rudder, a spherical angle joint was used to connect each inflated element to the base. It was anticipated that this type of angle joint could provide a solid and flexible anchoring to the base. The angle joints are compliant with DIN 71802 standards and feature a ball stud. The ball socket, designed with a female thread, and the ball stud, featuring a male thread, facilitated easy integration with other components, with a pivoting angle set at ±18°. These joints are bolted to triangular-shaped steel plates, which are welded to the 13-edged ring beam placed underneath. Overall, the ring beam and triangular plates remain underwater, while the inflated elements are "elevated" just above the water level [Figure 8]. To reduce the costs and the overall weight of the structure, it was decided to avoid using individual rigging screws for each vertical cable. Instead, a single screw was inserted into a steel plate with holes, welded on either side of the 13-edged ring beam beneath the waterline. This setup facilitated a one-side tensioning process for each of the individual 8mm diameter steel cables.

Figure 8: Lower node connecting the inflated steel elements and the ring beam [©Enrico Pontello].

6.0. Assembly on site

The assembly of the artwork required a sequence of steps to ensure the structural integrity and aesthetic coherence of the final piece. It began with anchoring the refined 13-edged ring beam to the concrete bed of the fountain using M8 x 100mm tilting adjustable feet with a 55mm base, which have a ball and socket joint attaching the base to the thread. This design allows the feet to serve not only as height adjusters but also to accommodate the uneven surface on the concrete bed. A scaffolding structure consisting of four equally spaced towers was erected to support a 13-edged aluminium ring formwork and facilitate the attachment of the top part of the inflated element to the hook.

After the sealing resin had dried, the inflated elements were bolted to the triangular plate using an M14 anchoring system and an M14 threaded rod, which prevents rotation while allowing the element to adjust its position [Figure 9]. Subsequently, the horizontal upper cable connecting all 13 elements was secured using a single rigging screw, enabling simultaneous tensioning of all the elements. Following this, each individual element was tensioned with vertical steel cables anchored to the ring beam. After dismantling the scaffolding, the fountain was refilled.

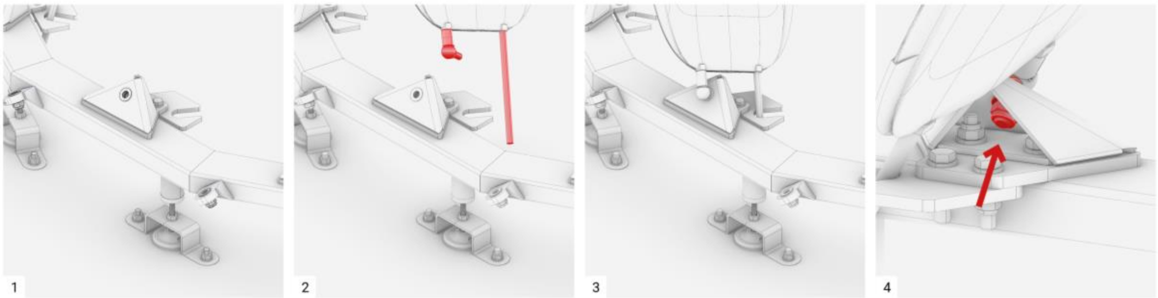


Figure 9: Lower node connection assembly phases.

7.0. Conclusions

The paper presented the innovative process behind the creation of the first-ever permanently built tensegrity artwork utilizing free-form inflated steel elements. The case study demonstrated the successful integration of tensegrity principles with inflated steel elements to provide a visually compelling artwork [Figure 10]. Inflated steel elements, optimized through computational design, have proven to be a mechanically robust solution. In the current study, the use of inflated steel elements has been limited by the crafting abilities of the parties involved, thus reducing the potential in scalability for commercial purposes. On the other hand, the production of bespoke shapes provided the opportunity to fully capture the essence of the Palio del Golfo and to create an aesthetically appealing artwork for locals and visitors. Furthermore, inflated elements open new scenarios for the creative exploration and the sustainable design in the built environment.

Incorporating inflated techniques into sustainable design offers a compelling pathway towards resource efficiency and environmental responsibility in construction. By utilizing inflated steel elements or pneumatic structures, architects and engineers can achieve lightweight, adaptable building solutions that minimize material usage and energy consumption. Additionally, these methods can facilitate rapid construction processes, reducing overall project timelines and on-site energy demands. The team of architects and engineers involved in the project continues to explore and refine inflated techniques within sustainable design, and anticipates significant contributions towards achieving more resilient, eco-friendly built environments for future generations. Future developments will focus on further experimentation and refinement, paving the way for even more ambitious and impactful architectural interventions.

Figure 10: Completed Artwork with inflated steel elements, enjoyed by locals and visitors [©Enrico Pontello].

Acknowledgements

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