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Lumen tensegrity towers

Kristen M. STROBEL*, Clayton B. BINKLEY, Jenny E. SABIN[a]

*Arup
719 2nd Ave, Suite 400, Seattle, WA, 98104
Kristen.Strobel@arup.com

[a] Jenny Sabin Studio & Cornell University

Abstract

This paper describes the structural engineering design, fabrication, and construction of three tensegrity towers installed in the courtyard at MoMA PS1 in Long Island City, New York during the summer of 2017. The towers were part of the 2017 Young Architect's Program installation, Lumen, designed by architect Jenny Sabin Studio and fabricated by Jacobsson Carruthers and Diamond Nets. Arup provided structural engineering design and form finding for the project. The towers were constructed of polyester rope with a steel mast, center ring, and base. The procedure for form-finding analysis of the towers, design and detailing of the towers to accommodate tensioning, fabrication tolerances and movement of the structure, and challenges encountered during fabrication are discussed. The compressed schedule and limited budget for the installation forced novel detailing to allow for offsite prefabrication, efficient assembly and tensioning, all while meeting the requirements for an outdoor installation in a public space visited by thousands of people.

Keywords: Tensegrity, Form Finding, Rope Structures, Sculpture, Structural Engineering, Textiles

1. Introduction

Three steel and polyester rope tensegrity towers were installed in the courtyard at MoMA PS1 in Long Island City, New York during the summer of 2017 as part of the comprehensive installation, Lumen, winner of MoMA & MoMA PS1's YAP program. The towers were designed by architect Jenny Sabin Studio and fabricated by Jacobsson Carruthers and Diamond Nets with structural engineering by Arup.

Lumen builds upon six years of design development at the intersections of knitted textiles, bio-inspired design, and architecture. Through six built projects and commencing with the myThread pavilion in 2012, a commission from Nike Inc., Jenny Sabin and her team have explored generative design and digital fabrication in knit and woven structures through multi-sensory responsive environments [1]. In recent projects, such as PolyThread for the 5th Design Triennial, *Beauty*, at the Cooper Hewitt Design Museum in collaboration with Arup, active bending and double surface formations were explored with a careful attention to the performance of the knit fabric and the supporting structure. Having designed, fabricated, and built five previous projects featuring responsive structural fabrics composed of individually digitally knit cellular components and cones, Sabin felt confident that the material system was ready to be pushed to the scale of the MoMA PS1 courtyards and an outdoor environment visited by thousands of people. Conceptually, we were interested in a structural system comprised of three towers that would: 1) maintain a consistent language with the geometry and form of the knitted cones comprising a large portion of the textile canopies; 2) explore the formal and structural potentials of textile-based structures and active tension systems at all scales of the project; 3) operate as a spatial connection between the grounds of the courtyards and the upper canopies; 4) be inhabitable and offer additional programmed areas such as for ticket sales; and 5) materialize at a large scale ongoing research on the relationships between biology, adaptive architecture, and tensegrity [2], [3].

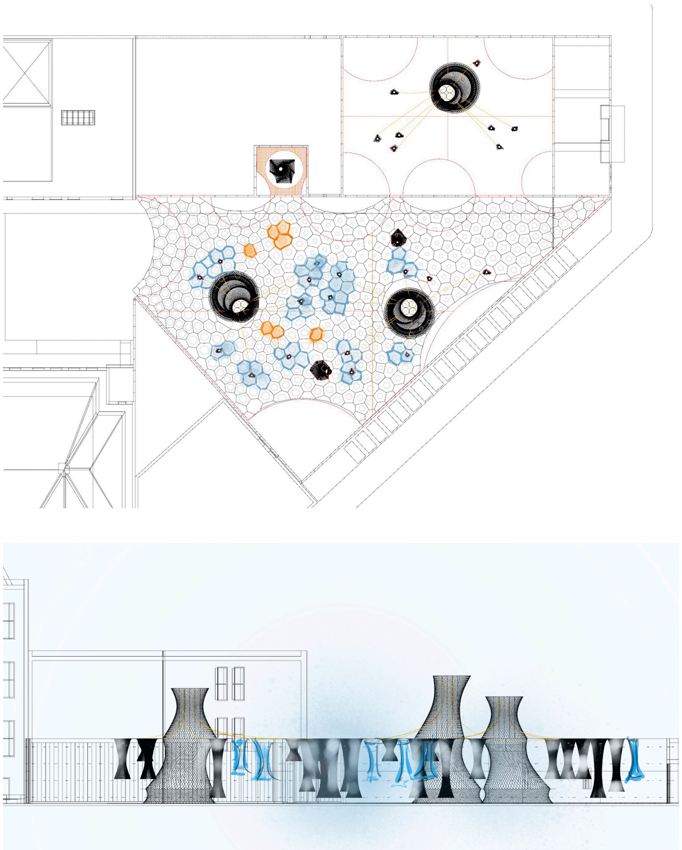

Figure 1: Early concept drawings by Sabin for the tower and canopy design

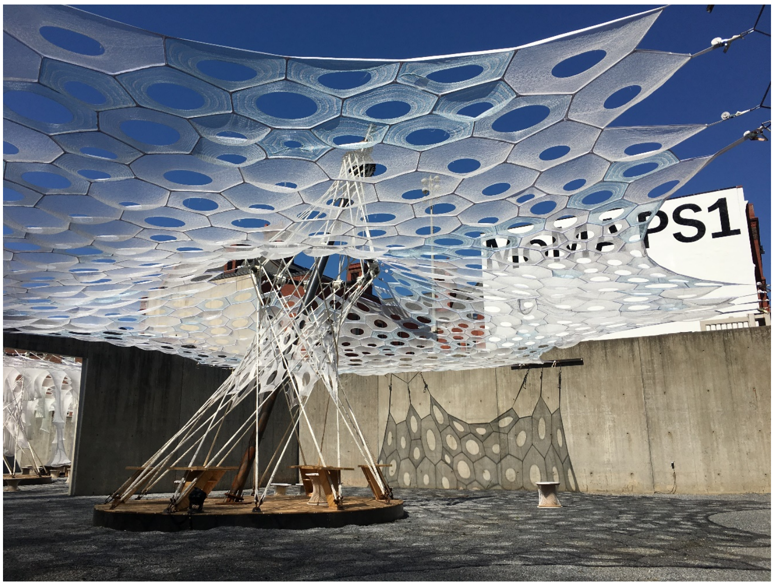

Figure 2: Tower 3

Each of the towers is comprised of five primary elements: a central steel mast, a suspended steel ring at the mid-height of the towers, a steel base built up from wide flange beams and channels, custom CNC flooring for the base, and 48 25 mm (1 in) polyester ropes. Each of the polyester ropes winds 120 degrees around the circumference tracing a hyperboloid of one sheet above and below the central flying ring. The towers have a single plane of symmetry about the mast; the bottom of the mast is offset from the center point of the base and leans back across the base (See Figure 3). While comprised of the same primary elements, each of the towers is geometrically unique having varying heights and angles of lean (see Table 1).

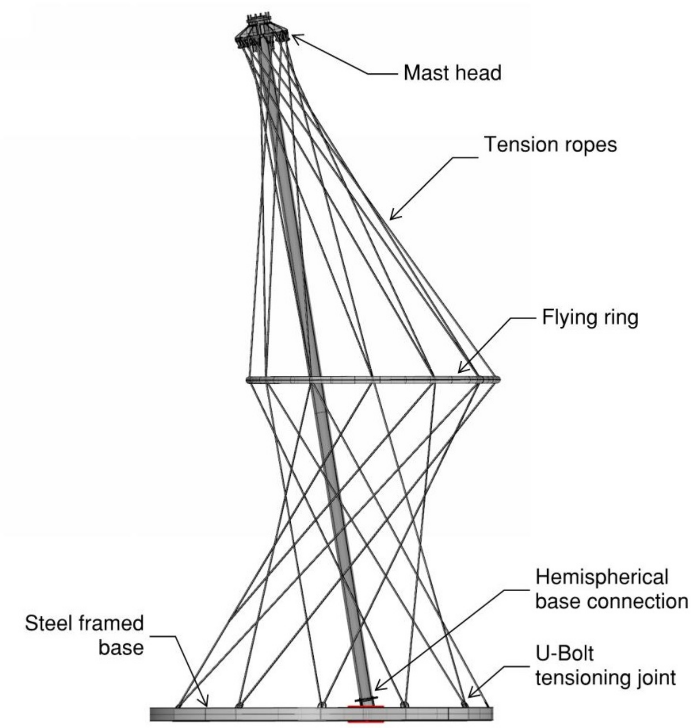

Figure 3: Tower Elevation

Table 1: Tower Geometry

Tower	Mast Height	Mast Angle of Lean	Mast Offset	Base Diameter	Center Ring Diameter
1	11.1 m (36’ – 4”)	9 degrees	74 cm (29”)	5.5 m (18’)	4 m (13’)
2	11.1 m (36’ – 5”)	10 degrees	86 cm (34”)	5.5 m (18’)	4 m (13’)
3	8.6 m (28’ – 3 ½”)	19 degrees	48 cm (19”)	5.5 m (18’)	2.75 m (9’)

The base of the towers works in flexure, resolving the tension of the ropes and the compression of the mast through a series of spokes that connect from each of the rope anchor points to the base of the mast. A compression ring around the outside edge braces the ends of the spokes against each other. Overturning under lateral loads is resisted by filling the base with gravel ballast.

2. Design

2.1 Design Concept

The design of the towers, in particular their realization as tensegrity towers, arose out of their relationship with the rest of the installation as well as ongoing research between the dynamic nature of textile structures, adaptive architecture, biology, and tensegrity. The tower’s primary purpose is to support two larger tensile canopies that spanned the courtyards at PS1. The tensile net was connected to and tensioned against the tower’s flying ring; creating a node in the net with the tower that served as a space to be programmed and occupied by the installation’s visitors. The towers were originally conceived as woven structures that create spatial, structural, and inhabitable connections between the ground and the upper canopies. They were intended to emulate the nature and form of the hanging knitted cones within the canopy and the dynamic textile-based architecture of the entire project (See Figure 1). Early conversations between Sabin and Binkley about the materialization and structure of the towers oscillated between actual woven structures such as the ‘hollow ropes’ of Robert Le Ricolais and rigidly framed structures similar to Shukhov’s towers [4], [5]. As the entire project evolved, we realized that there was an opportunity to construct the towers as tensegrity structures, to literally weave with forces; playing off the tensile character and performance of the net canopies that they supported. The vertical pretension that stabilized the towers literally added a third dimension to the overall envelope of forces that shaped the installation, thus bringing ideas of performance and adaptation to all scales of the project.

2.1 Modelling

Form finding for the towers was performed using a non-linear finite element model in the structural analysis software package, GSA [6]. Each of the towers was modelled using beam elements and tension only elements to model the steel elements and rope elements respectively. Due to the asymmetry of the towers, each of the ropes are of different lengths and have different prestress forces. To determine the variation of prestress in the ropes analysis was performed in two stages. First, using the intended final geometry a lack of fit was applied to the central mast to lengthen it and induce tension in the ropes (a similar action to jacking the mast). This provided the varying tensions required to keep the tower in equilibrium. Subsequently, these tensions were applied as prestress forces in the ropes starting from the target final geometry to perform form finding and determine the forces in each of the elements under various load combinations. Using this method, we minimized mast lean during the form-finding process and achieved a final form-found geometry that was sufficiently close to the desired target geometry.

The towers were designed for self-weight, prestress, wind loading, a live load of 1335 N (300 lb) applied at varying points around the central ring, and an eccentric load at the middle ring caused by the net hanging between the towers and the courtyard walls. To ensure that the towers maintained stability under the various loading conditions, rope pretensions were increased until all the ropes remained in tension under all load combinations. This resulted in prestresses varying from 3.6 to 18.3 kN (800 to 4115 lb), with peak tensions in the ropes under allowable loads of 22.6 kN (5085 lb).

The analysis of the tower and the base were performed separately to allow the models to converge more quickly. In the tower analysis model, the mast and ropes were all pinned at the base and these reactions were applied as loads in the base model to determine the forces in the base members and verify the stability of the base. To prevent the tower from overturning under lateral load, the base is filled with gravel ballast.

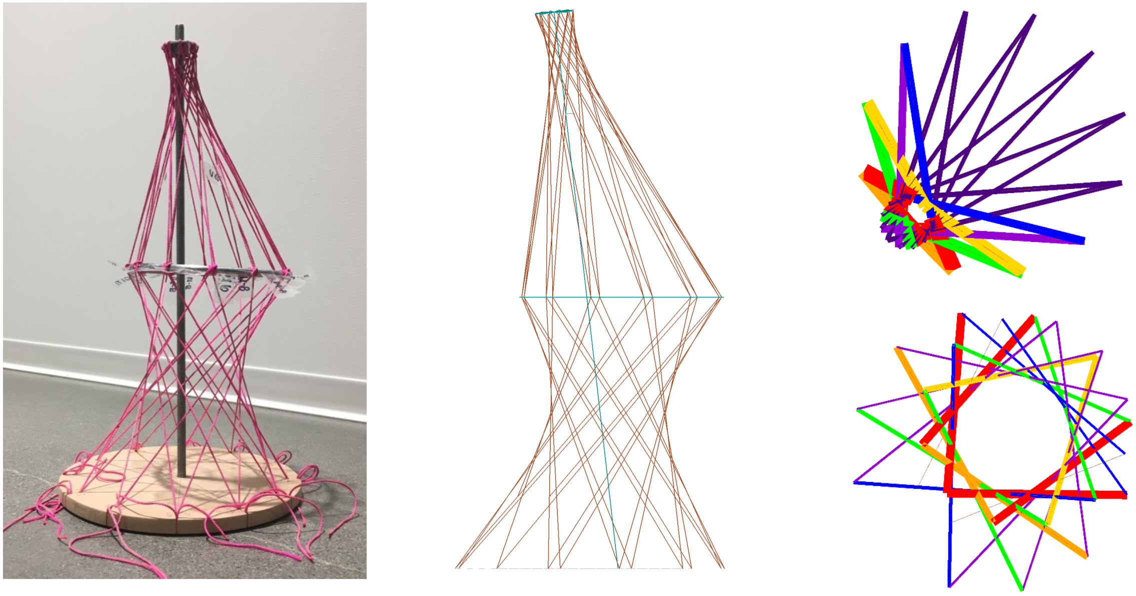

Figure 4: Scale model (left); analysis model (middle); variation in rope tensions at top and bottom (right)

To verify the design concept, a 1:48 (1/4” = 1’) scale model was constructed. This provided a simple verification of the stability of the structure and the design procedure. This also allowed us to gain insight as to the potential failure modes of the towers and overall robustness of the design simply by pushing on the mast and observing the resulting deformations. The model was also used to assess the geometry of the towers from an aesthetic perspective; in particular the balance between the mast angle and the resulting overall form of the tower.

In addition to the design described above, a number of sensitivity analyses were carried out on the tower to ensure that deviations from the design would not result in structural failure. Some of the variables tested include: variations in rope lengths, variations in pretension, and an investigation of the maximum lateral loads that the tower could sustain before it became unstable.

2.2 Materials

The structural properties of rope are well documented by rope manufacturers as rope is commonly used for load critical applications such as rigging. Based on manufacturer guidance and industry standards, the ropes are designed with a safety factor of three [7]. The allowable tensile strength of the rope is taken as 50 percent of the minimum tensile strength to account for the reduction in strength associated with local stress concentrations at connections [7]. Polyester rope behaves non-linearly, stiffening with increased loading. Rather than including full non-linear material properties in the analysis, ropes are designed using the modulus of elasticity at prestress. For the 12-strand polyester ropes used this equates to a modulus of elasticity of 1.3 GPa (190 ksi) and an allowable tensile strength of 30 kN (6800 lb).

Rope fabrication lengths are given as slack lengths. Slack lengths are derived from the stressed lengths and prestresses in the analysis model using Equation 1. For the most stressed ropes, this leads to a stretch of 16.5 cm (6.5 in) between the slack and fully prestressed conditions.

$$\mathrm{L}_{slack} = \left. \frac{\mathrm{E}*\mathrm{A}*L_{stressed}}{Prestress} \middle/ 1 + \frac{E*A}{Prestress} \right. \tag{1}$$

Slack lengths from the model are adjusted to account for the length of connections and offsets between rope endpoints in the analysis model and the actual endpoints in the built condition.

3. Detailing

The detailing of the towers is designed around erection of the tower. The towers are designed to have both coarse and fine adjustment of tension to both tension the entire tower and accommodate fabrication tolerance of the ropes. The limited budget for the project drove unique detailing that avoided typical tension connectors, such as turnbuckles, that were too expensive for the project budget in the quantities required.

3.1 Mast Base

Under wind loading, the top of the tower deflects up to 38 cm (15 in) laterally. To allow the tower to sway without inducing flexure in the mast and base, the bottom of the mast is pinned. This is achieved by detailing the mast base using a flange with a hemispherical profile cutout that mates with a hemispherical base. The base hemisphere was created by machining a spherical surface into a 229 mm (9 inch) diameter solid steel round bar. The bar was mitered to align with the angle of the mast. This allowed the mast to rotate freely during stressing and when subjected to lateral loads while still transferring axial load into the base. Threaded rods in oversize holes prevent the mast from lifting off the base if unforeseen circumstances put the mast into uplift while still allowing it to rotate under normal loading conditions.

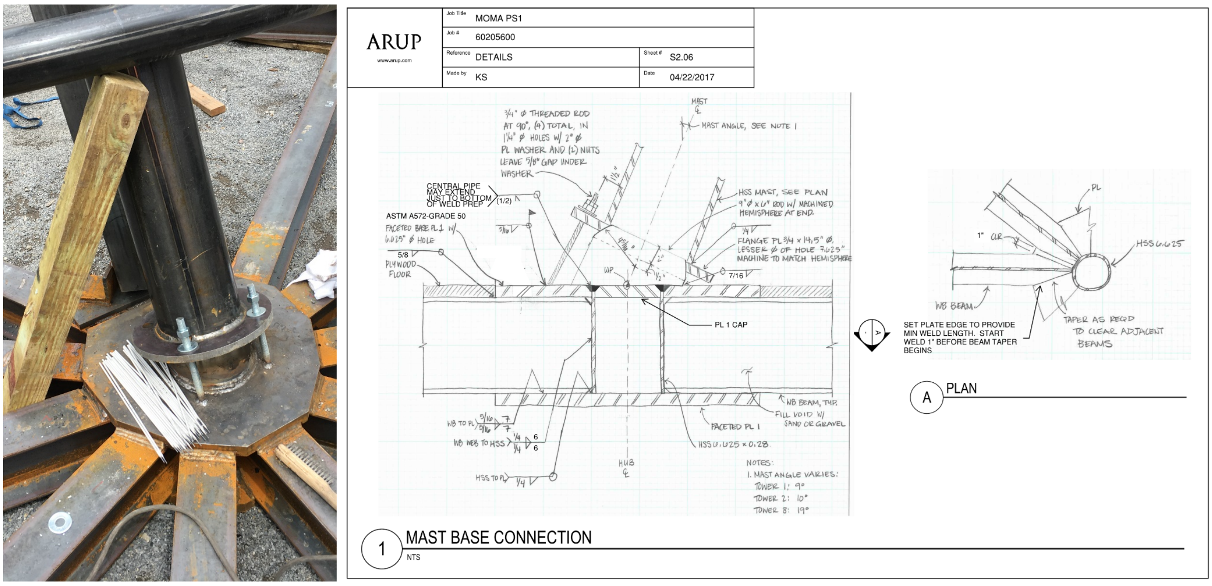

Figure 5: Mast base connection

3.2 Mast Top

Bulk tensioning of the towers was achieved using the mast top connection. The top connection consists of a collar, that slides over the central mast, and a flange fixed to the central mast. Six threaded rods run from the top of the collar through the flange. By spinning down the double nut at the top of the threaded rod, the collar is jacked up putting tension into the ropes. To coarsely tension the entire tower, the collar needed to be jacked 30 cm (12 in).

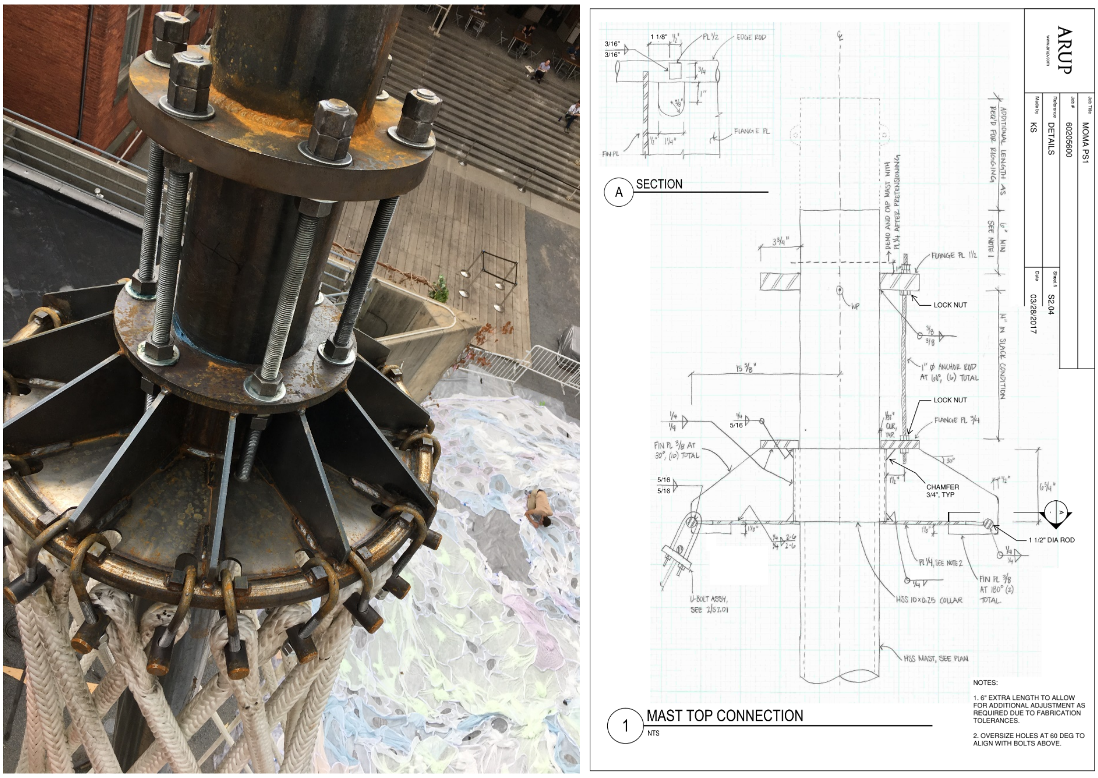

Figure 6: Mast top connection

The diameter of the top connection was set by two competing variables: maintaining a small diameter to limit flexure in the collar and maintaining a large enough diameter to limit congestion of the ropes and their hardware. To achieve the necessary clearances, the U-bolts at the top connection are shorter than those at the bottom relying on the increased travel at the bottom of the tower to provide most of the fine adjustability in the system.

3.3 Rope Details

At the top and bottom of the tower, the ropes are attached to U-bolts. By tightening down the nuts of the U-bolts, the tension in the ropes can be individually adjusted to account for fabrication tolerances in the length of the rope. The U-bolt allows the rope to pivot in all directions relative to the anchor point minimizing flexure through the connections. To prevent kinking of the fibers of the rope, and a resulting loss of capacity, ropes need to be wrapped around an object with a diameter that at a minimum matches the diameter of the rope. This drives the size of the U-bolt crossbar to be larger than it would need to be if solely designed for flexure. The steel fabricator was able to find a supplier who could produce the custom hardware required at less than one tenth the cost of turnbuckles.

At the middle of the tower, the ropes are anchored off with the rope looped around the pipe and through its own eye. This allowed the towers to be laced around the middle ring at ground level and then attachments made to the U-bolts at the top and bottom of the tower. Opposing pairs of ropes are crossed to allow shear to transfer between the ropes and to keep them centered within the connection zone.

Figure 7: Rope connection at ring (left); rope connection at base (right)

4. Fabrication and Construction

Sequencing of the tower installation was as follows. First, the steelwork was set into place and the mast was propped into place using a temporary support.

Each of the ropes were pre-stretched to a tension of 26.7 kN (6000 lb) prior to installation. This allowed for constructional stretch and bedding in of the eye splices, resulting in approximately 30 cm (12 in) of elongation to the ropes from their fabricated length. By prestretching the ropes beyond the ultimate load, excess lengthening of the ropes under stresses above the initial prestress is prevented.

Once the ropes were pre-stretched, ropes were laced around the middle ring at ground level. The ring was then lifted and the top connections were made, followed by attachment of the bottom connections. Once the ropes were fully connected, the top connection was jacked up taking up the elastic stretch of the rope and bringing them close to the required prestress. At this point, the mast lifted off its prop, and the towers were freestanding.

Next, the tension in the ropes were finetuned using the U-bolts to increase and decrease tension while monitoring rope tension with a tension meter to achieve the required prestress. Prestress was adjusted to within a tolerance of 0.5 kN (100 lb). Once the tower was fully tensioned, the top of the tower was pushed back and forth to rotate it about the base forcing the ropes to settle into their final locations. The towers were also left for one to two weeks to allow the ropes and splices to further "bed in" and lose some of their pre-tension. Following this, the tension in each of the ropes was measured again and additional adjustments to rope tensions were made.

While installed, ongoing monitoring of the towers was performed to ensure the ropes were not losing tension due to further constructional stretch in the rope or connections. Ongoing monitoring was performed by measuring the angle of lean of the mast on a weekly basis. Mast lean angle was found to be an accurate indicator of the overall level of pre-tension in the structure. Over the three months of the installation the masts were found to not move significantly and no additional adjustments were required to the tension in the ropes.

Figure 8: Erection sequence: ring laced (left); ring laced with top connections (center); Fully installed [photo courtesy: Pablo Enriquez] (right)

5. Conclusion

The success of this project relied on careful analysis, detailing, fabrication, and collaboration. In analysis, a thorough consideration of possible failure modes and sources of inaccuracy generates a robust structure. Concept verification through physical modelling provided a quick way to understand the behavior of the structure and ensure the analysis model was representative. By detailing the structure to accommodate fabrication tolerances, variation from the design tensions was minimized. The connection details were designed to match the modelled boundary conditions, allowing the structure to move under loading while minimizing flexure through the supports. In fabrication, measurement of tension ensured the ropes were meeting the specification.

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