Rokko Mountain Observatory

Location
Kobe, Japan

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Using innovative purpose-designed software, Arup undertook the detailed design of this irregular meshed dome, an observatory for visitors to experience a spectacular mountain environment.

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1. The Rokko Observatory.

2. Three-stick model.

3. First study model of the shifted frame system using chopsticks.

4. Basic parametric model.

2.

Introduction

In late 2008, a design competition was held by the project promoters Hanshin Electric & Rail Corporation for a new observation point built at an altitude of some 900m on a peak of the Rokko Mountains in Kobe, Japan. This observatory was to be a place not merely for visitors to pause and take in a spectacular view, but a destination in itself, a location specifically designed to aid and enhance a more profound experience of the natural energy and beauty of the Rokko Mountains (Fig 1). Hiroshi Sambuichi Architects' unorthodox design approach proved victorious in the competition, with Arup providing geometric and structural engineering and environmental design support from the outset.

The observatory's key visual feature is its intricately meshed dome, 16m in diameter, which provides partial shelter against the weather as if by tree branches and foliage. As well as this, the environmental design has two principal aspects. Firstly, the observatory is shaped so as to passively induce air movement for natural ventilation. Secondly, winter ice that freezes in water paddies around it is stored in insulated compartments until summer for passive cooling.

Structure

The shape

The architect's first competition sketch showed a delicate network of branch-like elements forming the outer skin of the observatory space, a skin to control but not completely block sunlight, rain/snow, and wind. Arup immediately saw that the interwoven network should somehow be self-supporting – geometrically complex, but simple to construct. Constructional practicality and budget constraints were key factors.

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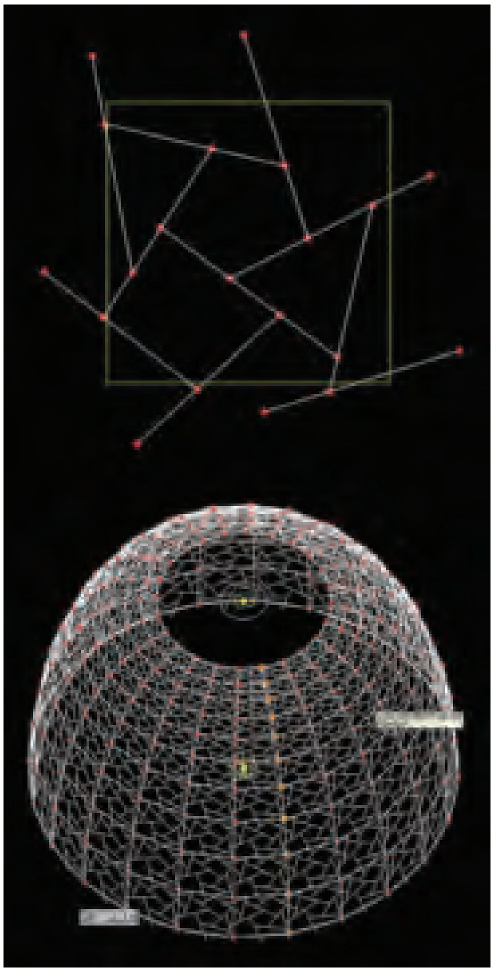

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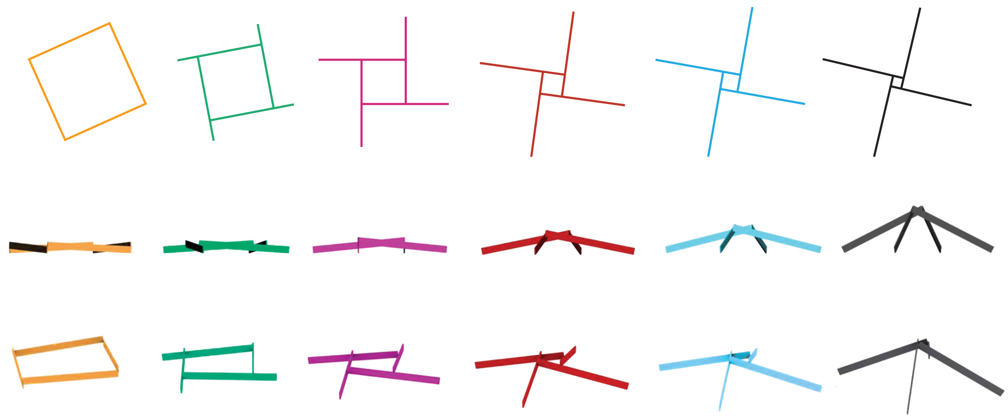
Systems of stacking and/or weaving short elements to span large spaces have existed for a long time. One example is the class of self-supporting structures called reciprocal frames[1], the simplest of which is the three-stick model (Fig 2). Another and more evolved type of layered structural system has been used for many Japanese timber temples and shrines. With such historical examples in mind, Arup developed a system that could be assembled simply by interweaving small, lightweight elements, without special connections or fabrication technologies (Fig 3).

Initial competition modelling

Based on the initial chopstick model study, a unit pattern of intersecting elements was defined in Bentley's *GenerativeComponents* program, and associated to the surface of a multi-faceted cylinder that could be manipulated parametrically (Fig 4).
The elements were not at this stage interwoven, but remained flat on each facet of the surface.

The team used this parametric model to investigate the appropriate density of the elements forming the dome, in terms of structural needs and visual impact, and reached decisions that remained constant: there would be a main structural frame in 50mm diameter steel tubes, 1m-2m long, with a finer mesh of 15mm-20mm diameter wood bars (Japanese cypress) attached within.

The team was confident that this new system could work, but also understood that defining the geometry of the interwoven elements would be very complex.
A completely new geometric solver would have to be developed to manipulate and accurately define the complex geometry of this shift frame system, should the Sambuichi/Arup design win the competition – which it did.



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Towards the geometry

Stacking and weaving the elements naturally shifts the entire frame out of plane, so that it becomes warped in three dimensions. The extent of the out-of-plane shifting depends directly on element thickness and the position of adjacent elements (Fig 5). As the process of stacking and weaving is repeated, the geometry becomes impossibly difficult to predict by conventional means.

But on the other hand, if the shifted geometry of the frames can be calculated and determined, this implies that the form can be manipulated to best fit any desired surface shape. To enable this, the team undertook to derive a numerical solution to solve the shifted geometry of the interwoven elements.

The first step was to define the vector and distance between adjoining cylinders in relation to the directional vectors of the cylinders themselves. It was soon realised that the vector that defines the minimum distance between the axes of two cylinders is also at right angles to those axes. Based upon this vector relationship, an extensive matrix of simultaneous equations could be formulated and then solved.

Since the geometry of the whole depends on the shift of each element, the solver program must be iterative. As the calculation becomes exponentially larger for each element introduced, even with current computational power the prototype solver would take hours for the solution converge. The method clearly had to be streamlined so as to be more parametric and more accurate, but still with less computing time so as to satisfy the project constraints.

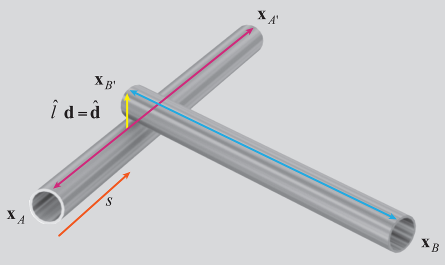
The solution

After several months of development, a program which became known as the shift frame geometry (SFG) solver was formulated (Fig 6). Simply put, the SFG solver incrementally shifts each element simultaneously towards the predefined side (over or under the element) and iterates the process until the solution converges – the solution being the actual shifted geometry.

The condition of a properly shifted joint can be expressed in two different vector equations (1) and (2), which are then equated together by the relationship in equation (3). If equation (3) is satisfied, this means the elements are properly shifted. Since combining every element assigned to be on the top, the bottom, or along the length would result in vast numbers of permutations mostly without any rationale, an optimisation condition was introduced into the solution to find a single combination that would result in the shortest total element length – the combination that results in the flattest shift frame (equation 4).

Equation (5) is the non-linear equation to locate the nearest optimal point. Finally, to solve the non-linear equation and significantly speed up the convergence (computation time), the Newton-Raphson method was employed (equation 6) – an efficient method for finding successively better approximations to the zeroes (or roots) of a real-valued function.

With the advent of the SFG solver, it suddenly became possible to convert any surface pattern of any sized elements into a desired shift frame form with complete geometric accuracy (Fig 7).



(1) Distance vector.

$$\mathbf{d} = -\left(\mathbf{x}_A + \left(\mathbf{x}_{A'} - \mathbf{x}_A\right) - \mathbf{x}_B\right)$$

(2) Distance vector.

$$\hat{\mathbf{d}} = \hat{l}\ \frac{\left(\mathbf{x}_{A'} - \mathbf{x}_A\right) \times \left(\mathbf{x}_{B'} - \mathbf{x}_B\right)}{\left(\mathbf{x}_{A'} - \mathbf{x}_A\right) \times \left(\mathbf{x}_{B'} - \mathbf{x}_B\right)}$$

(3) Boundary condition.

$$\mathbf{d} - \hat{\mathbf{d}} = \mathbf{0}$$

(4) Conditional optimisation.

$$\min \pi \text{ s.t } \quad \pi = \sum_{j=1}^{n} l_i + \sum_{j=1}^{m} \boldsymbol{\lambda}_j \left(\delta \mathbf{d}_j - \delta \hat{\mathbf{d}}_j\right)$$

(5) Optimal point derived using variational method.

$$\delta\pi = \sum_{j=1}^{n} \delta l_i + \sum_{j=1}^{m} \delta\boldsymbol{\lambda}_j \left(\mathbf{d}_j - \hat{\mathbf{d}}_j\right) + \boldsymbol{\lambda}\left(\delta\mathbf{d}_j - \delta\hat{\mathbf{d}}_j\right) = \begin{pmatrix} \delta\mathbf{U} \\ \delta\boldsymbol{\Lambda} \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} \mathbf{Q} \\ \mathbf{D} - \hat{\mathbf{D}} \end{pmatrix}$$

(6) Tangent matrix using the Newton-Raphson method.

$$d(\delta\pi) = \begin{pmatrix} \delta\mathbf{U} \\ \delta\boldsymbol{\Lambda} \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} \mathbf{K}_e & \mathbf{K}_\lambda^{\mathrm{T}} \\ \mathbf{K}_\lambda & \mathbf{0} \end{pmatrix} \begin{pmatrix} d\mathbf{U} \\ d\boldsymbol{\Lambda} \end{pmatrix} = \begin{pmatrix} \delta\mathbf{U} \\ \delta\boldsymbol{\Lambda} \end{pmatrix}^{\mathrm{T}} (\mathbf{K}) \begin{pmatrix} d\mathbf{U} \\ d\boldsymbol{\Lambda} \end{pmatrix}$$

Key

$\mathbf{x}_i$: vector of elements $\mathbf{d}$, $\hat{\mathbf{d}}$: shift vector

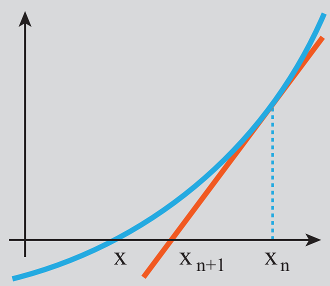
s : joint location parameter $\hat{l}$: offset amount l : element length

π : total length of vectors n : number of elements

m : number of joints $\boldsymbol{\lambda}$: Lagrange multipliers

$\mathbf{K}$: tangent matrix

Newton-Raphson Method



One starts with an initial guess which is reasonably close to the true root, then the function is approximated by its tangent line (which can be computed using the tools of calculus), and one computes the x-intercept of this tangent line (easily done with elementary algebra). This x-intercept will typically be a better approximation to the function's root than the original guess, and the method can be iterated.

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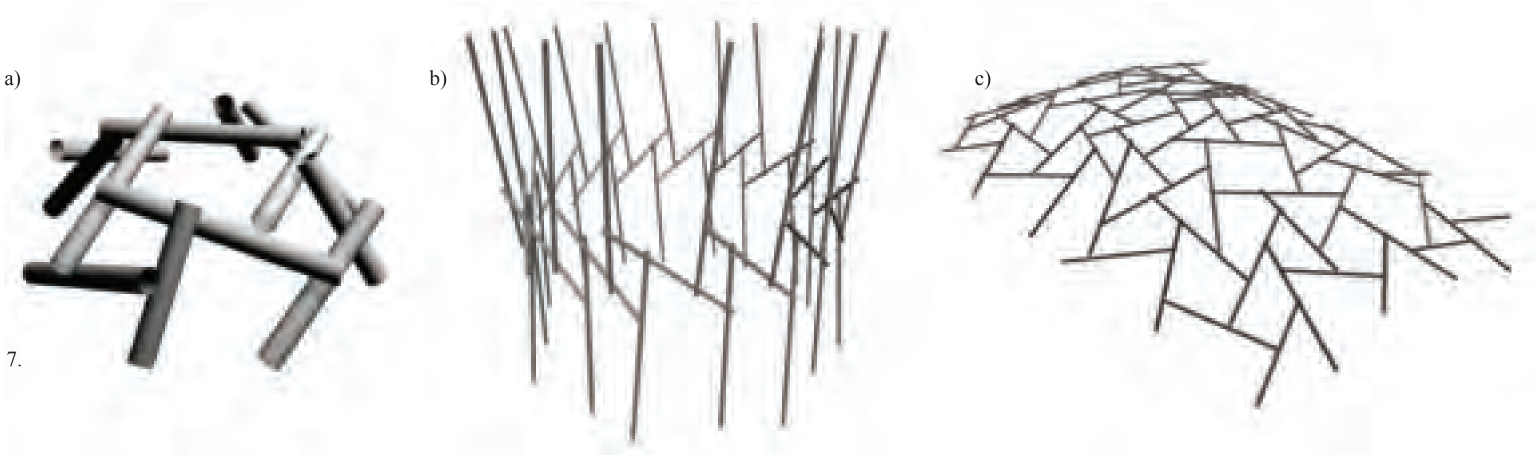

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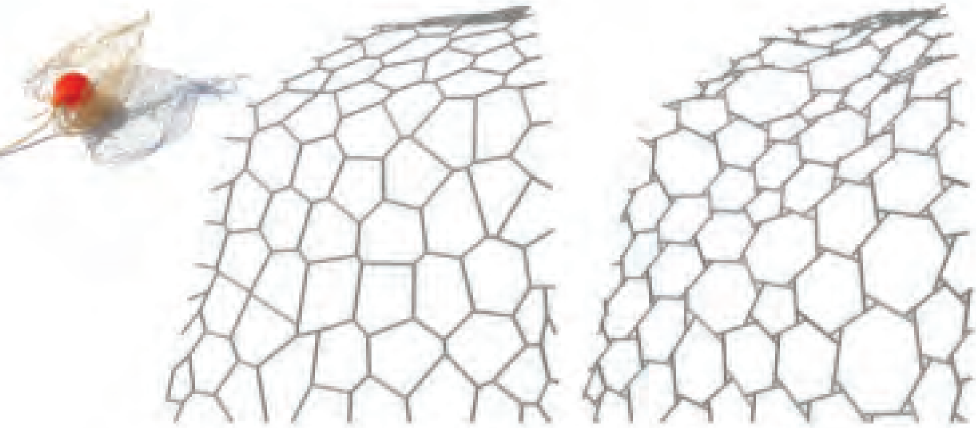

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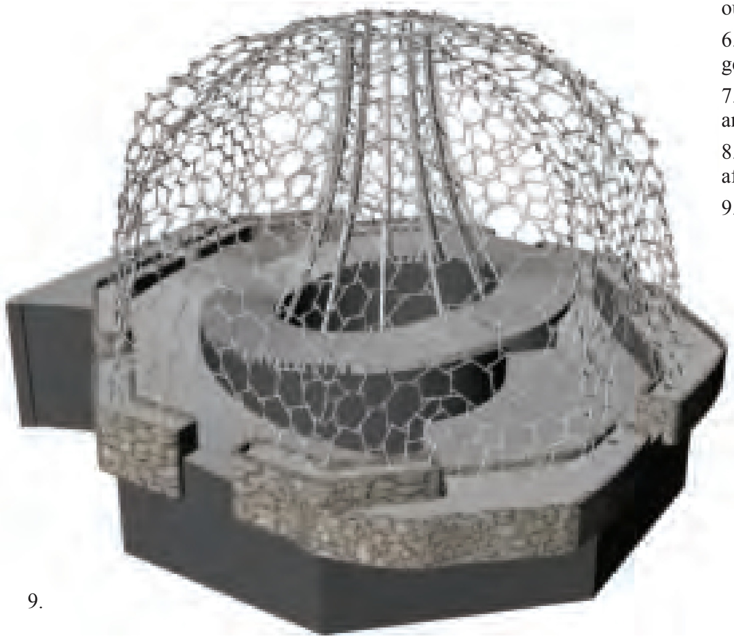

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5. Differences in the extent of out-of-plane shifting.

6. Overview of the shift frame geometry (SFG) solver.

7. Variations of SFG patterns and forms.

8. Voronoi tessellation before and after running the SFG solver.

9. Final form of shift frame dome.

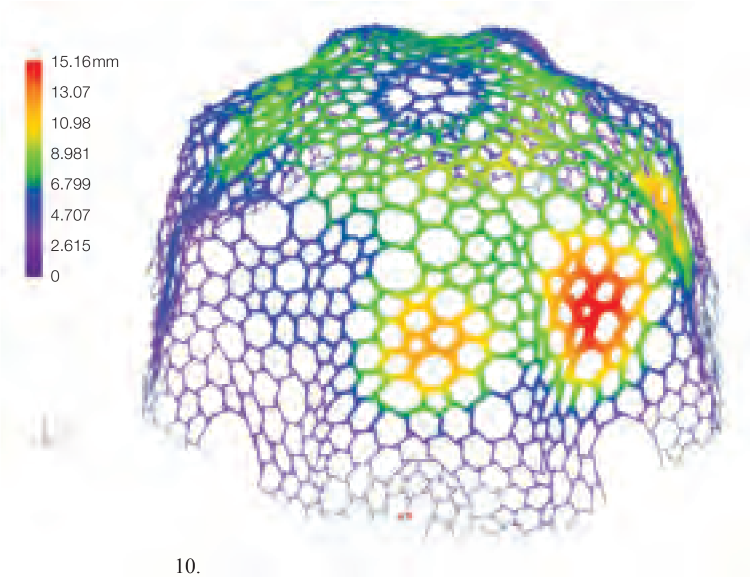
The design realised

Reverting to the design of the observatory itself, after several rounds of discussion with the architect, the pattern of the shift frame changed. Rather than it being an arbitrary formation of interwoven elements, the team agreed that patterns akin to those found in nature would be more appropriate to the overall concept, so the final pattern was based on Voronoi tessellations.

These relate to a set of points in space, the tessellation boundaries occurring midway between adjacent points. On a two-dimensional surface, the boundaries can be created by drawing perpendicular bisectors to the lines joining those points; three, or in special circumstances more, of these bisectors intersect to give the corners of the tessellations.

A separate program was quickly developed to generate Voronoi tessellations on a three-dimensional surface, and then the SFG solver was used to convert the faceted Voronoi pattern into a shift frame comprising hexagons and triangles (Fig 8). The density of the tessellations was adjusted according to the required structural capacity of the whole system.

In the final form of the shift frame dome (Fig 9), each of the straight 50mm diameter steel tubes was reciprocally shifted and the contact points welded together. The resulting interwoven network of tubes forms a stable structure that can resist heavy snow and typhoon loads.



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10. Structural analysis results.
11. Assembling the shift frame.
12. Full scale mock-up testing.
13. Visitors enjoy the shade.
14. Environmental design concept.
15. Winter ice crystals on the dome.
16. *Himuro* ice storage compartment.

The generated geometry of the shift frames was imported into analysis software to verify structural integrity, and the results then fed back into the Voronoi generation step and reassessed. This process was iterated so as to optimise the dome's structural and visual impact. As the shifted geometry is accurately defined in the model, additional stresses due to the eccentricity of the tube centroids are also accurately reflected (Fig 10).

Construction

Due to the complex geometry, conventional 2-D drawings were clearly inadequate for construction purposes. While in theory the process of fabricating shift frames is merely to cut, place, and weld steel tubes, it was still critical that the fabricator be technically able to comprehend fully the 3-D geometry, so from the start the team worked closely with a highly skilled fabricator. To facilitate post-processing the geometrical data, the design team prepared, in addition to the 3-D model, a table defining the geometry of each individual tube.

The position of each shift frame element is highly interdependent, so if one tube was placed incorrectly, the next (or the one after) would simply not fit. Maintaining a high level of accuracy during assembly was thus crucial in completing this spatial puzzle.


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Fortunately, the fabricator proved to be exceedingly resourceful in devising new ways to measure and accurately position the tubes (Fig 11). Prior to bringing them on site, a full-scale mockup (Fig 12) was erected, which also included the smaller and more intricate wood shift frames attached to the larger steel structure.

Environmental design

Environmental function of the skin

The outer mesh has several environmental functions. First, its varying density creates a comfortable outdoor environment in the viewing space between itself and the central tower. The upper part of the south face is of high density, to reduce summer solar radiation, but the lower part is much more perforated to allow the passage of wind to keep visitors cool (Figs 13, 14). This improves visitor comfort especially here, as the observatory enjoys relatively mild summers due to its mountain-top location.

Second, in winter the mesh becomes a vehicle to exhibit the natural beauty of ice crystals (Fig 15). This ice coating, or rime, forms by water droplets in fog freezing when they touch cold surfaces. Freezing humid air and strong wind are indispensible for ice crystal formation, and Rokko is famous for this beautiful natural phenomenon.

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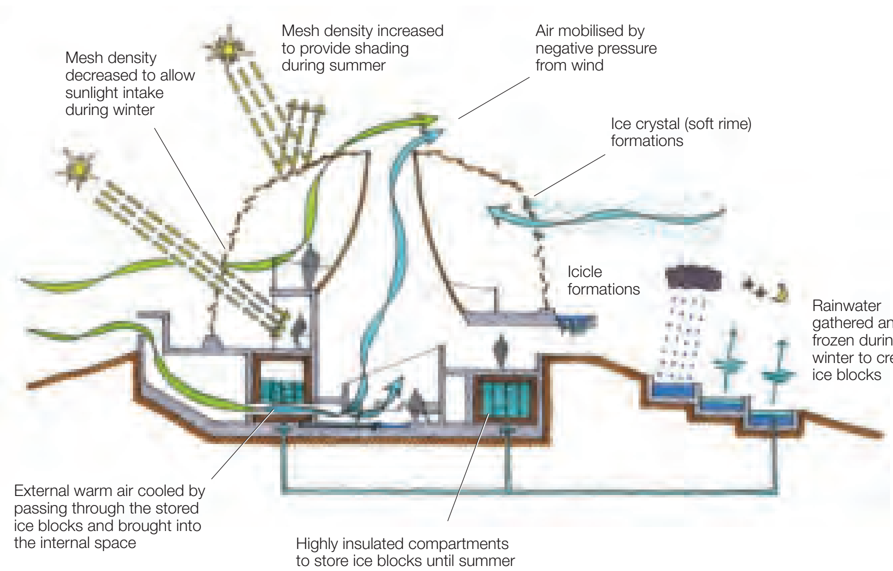

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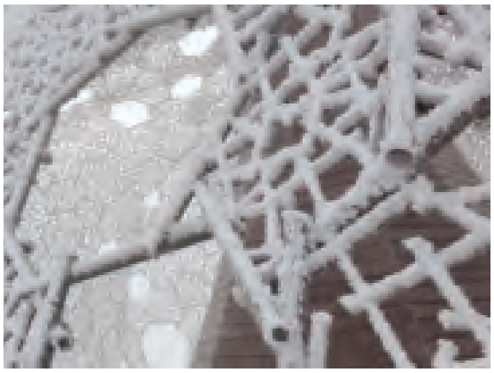

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The architects realised that this could happen on the mesh and asked Arup to incorporate any design elements into the mesh that could encourage ice crystal formation. Low surface temperature was necessary, and thermal analysis was carried out to establish the optimum material. A mock-up was then constructed on the site to test. These results showed that thin timber with low thermal capacity was best, as it rapidly follows any external temperature drop. Roughing the timber surface also aids ice crystal formation, and in addition the northern aspect of the mesh dome was designed and constructed to be less dense than elsewhere, increasing access to the strong north winds that form the ice crystals.

Stored ice for summer cooling: the "cooled breeze experience"

Rokko Mountain is well known for its natural water supply, and the observatory allows visitors to enjoy such spectacles as winter icicle formations or summer cascades. In addition, a "cooled breeze experience" for visitors was incorporated into the plan, using the ice that freezes naturally in winter.

At other times in the year, rainwater is caught in 200m^2 paddies arranged around the observatory, this size being arrived at through knowing the volume of ice needed for the cooled breeze experience, and the anticipated number of times of freezing, amount of rainfall, and rate of evaporation.

In this district, a natural ice-making industry once prospered, and even today enough ice is frozen for storage a few times per winter season. The ice is cut into blocks and placed in highly insulated ice storage compartments called *Himuro* in traditional Japanese. At the observatory, two 16m^3 *Himuro* are provided with 500mm thickness of insulation to keep the ice blocks frozen until summer – the thickness determined by the optimum cost and performance (Fig 16). The insulation has two layers, the inner being of calcium carbonate. This has low permeability and strong vapour resistance, so as to prevent liquid water from permeating the outer layer and lowering the overall performance of the insulation.

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17. Bench armrests, showing louvres.

18. Rokko observatory at night, and the view towards Kobe.

In summer, the ice blocks lower the temperature of incoming air, which becomes a cool breeze into the main room, the Fushitsu. At the design stage the team debated how best to introduce the cooled air for maximum visitor comfort, and a louvre in the bench armrests was determined as the most effective (Fig 17).

Taking into account climate data, the site characteristics and construction practicalities, it was determined that natural wind, shown by the data to be strong and stable at the mountain-top, would be adequate to maintain air flow over the ice. The design is focused on maintaining positive pressure at the inlet and negative pressure at the outlet. The inlet was thus located on the south side to capture the summer seasonal wind, but it was made open on all sides so as to draw air in from any direction. The outlet is at the top of the central tower ,where negative pressure is generated from any wind direction.

Air from the inlet blows down to the basement floor, and is cooled during passage through a duct at the bottom of the stored ice, designed so that liquid water drains off the edge. The length and size of duct was decided by cooling capacity and air movement resistance. The air generally cools by around 5˚C while passing through the duct at a rate of some 300m^3/hour. The volume of air moving naturally depends on the strength of the wind, and so the observatory staff control the size of the input opening to maintain the optimum air flow for cooling.

Completion

Opened to the public in July 2010, the Rokko observatory exemplifies the new possibilities for architecture in applying hi-tech analytical techniques to realising low-tech design solutions.

Nearing the first complete seasonal cycle of summer-autumn-winter-spring, well over 100 000 visitors have made the trip up the mountain to experience the changing face of the new observatory.

Authors

Kazuma Goto is an engineer with Arup in the Tokyo office. He led the geometric engineering for the Rokko observatory project.

Ryota Kidokoro is an Associate of Arup in the Tokyo office. He led the Arup project team from competition to completion.

Takeshi Matsuo is an engineer with Arup in the Tokyo office. He supported the architect in developing the observatory's environmental design aspects.

Project credits

Promoter: *Hanshin Electric and Rail Corporation*
Client and architect: *Hiroshi Sambuichi Architects*
Structural and geometric engineer and environmental designer: *Arup – Kazuma Goto, Ryota Kidokoro, Takeshi Matsuo, Yoshiyuki Mori* Steel fabricator: *Yajima Corporation.*

Image credits

1, 16-18 *Hiroshi Sambuichi Architects*; 2 *Nigel Whale*; 2-15 *Arup.*

Reference

(1) LARSEN, OP. Reciprocal frame architecture, Architectural Press, 2008.

This article is partly based on the paper "'Rokko Observatory' – Application of geometric engineering", by Ryota Kidokoro and Kazuma Goto, presented at the International Symposium on Algorithmic Design for Architecture and Urban Design, ALGODE TOKYO 2011, held on 14-16 March, 2011.