Engineering Marsyas at Tate Modern

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How it all began

Each year since opening in 2000, the Tate Modern[1] gallery in London has commissioned an installation sponsored by Unilever for the Turbine Hall, a vast interior space over eight storeys high and 150m long. In January 2002 the Tate approached the Turner Prize-winning sculptor Anish Kapoor to undertake the third in the installation series. The brief was entirely open, the only constraints being budget and that the work had to be completed by 8 October 2002, less than nine months from commission to unveiling.

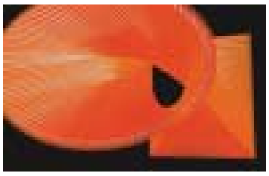
Kapoor, aware of the work that Cecil Balmond and Arup's newly-formed Advanced Geometry Unit were doing with such architects as Toyo Ito, Daniel Libeskind, and Shigeru Ban, arranged a preliminary meeting in late February 2002. At this time the artist was still wrestling with the immensity of the Turbine Hall as an art space. His predecessors, Louise Bourgeois and Juan Munoz, had elected to use only the eastern end, but Kapoor concluded that 'to tackle the verticality of the space one has to paradoxically take on its entire length'.

The offer was thus open for Arup to collaborate on a very special project. From the outset it posed huge challenges to both artist and engineers, but given the nature of Kapoor's organic curved forms and the sheer scale of the Turbine Hall, it was an offer the Arup Unit could not refuse, and they threw themselves into designing and delivering a piece of work that broke boundaries between architecture, art, and engineering.

Developing the concept

Arup explored many ideas (Fig 1) with Kapoor, ranging from a solid bean-like form that cantilevered outwards from the central mezzanine bridge, to a mirrored form stretching from one end of the Hall to the other, to the final choice of a complex membrane shape stretched between three steel rings. Within these primary concepts many sub-ideas were explored, such as the effect of air inflation, and of hydrostatic pressure created via the use of tonnes of polystyrene beads. Many material options were examined including plywood, PVC, expanded metal mesh, aluminium, GRP, and glass cloth laminated with metal films.

It was essential to developing the work that these ideas could be explored and visualized effectively and rapidly. A clear methodology was required. Complex 3D analytical models were built using software such as the in house, non-linear, form-finding program Fabwin, which was reprogrammed specifically for the project to help create the highly curved organic forms desired by Kapoor. The geometry of tensile membrane structures is based on that of a soap film stretched between boundaries, with the software simulating the behaviour of a natural soap film. Through the reprogramming the Arup team was able to push the form way beyond the soap film envelope of normal membrane structures and into new engineering territory.


a. Ellipse


b. Stretch


c. Peanut


d. Steel


e. Cleft


f. Double

1a-f. Some ideas explored during scheme development.

It was also apparent from the start that communicating the design ideas was paramount to the project's success, and so to visualize the forms as they developed, wax prototypes were built using the team's Thermojet printer (Fig 3). Thus complex geometry, not easily conveyed through conventional two-dimensional drawings, could be examined and more easily understood by Kapoor and the Arup team.

Finally, to demonstrate what the various forms would look like within the Turbine Hall space, Arup developed a '*Realtime*' virtual reality engine (see panel on right) using the latest 3D gaming technology. Models developed initially using analysis software were transferred directly into a virtual Turbine Hall, allowing Kapoor to 'walk' around the piece at his leisure using 3D glasses. Thus colour, texture, and lighting, as well as form, could be studied in detail. (The *Realtime* system proved such a useful and intuitive tool that it is currently being developed for use throughout Arup for all types of design projects.)

Using an iterative process of analysis, prototyping, and virtual reality, plus scale models from Kapoor's studio, the artist and engineers arrived at an optimum form.

The final design

After three intense months of developing and refining ideas, the team arrived at a final concept and outline geometry. In essence this was a membrane stretched the entire length of the Turbine Hall and anchored at each end to massive 30m diameter steel rings in turn anchored and propped by the fabric of the Hall itself. In the centre, hanging 2.5m above the central bridge, was to be a third steel ring, its weight and shape being used to contort the membrane and give more scope for defining the overall form (Fig 4). Removable panels were detailed into the central ring so that sand bags could be added for further ballast and to allow horizontal tuning of the ring's final position.

Engineering the membrane

Simply speaking, FABWIN treated the membrane surface as a net of node points connected by triangles. Each triangle tried to pull on its three corner nodes with a constant force (prestress), which in turn moved the nodes. This iterative process was carried out for every triangle and every node many hundreds - even thousands - of times until each node stopped moving because it was being pulled equally in all directions. Because the triangles pulled with the same amount in all directions, similar to a soap film, the resulting surface developed an equal amount of curvature in all directions. By varying the amount and direction of prestress within specific parts of the surface, the curvatures could be precisely tailored to create the forms desired by Kapoor, resulting in the dramatically long drawn-out 'backbone', 'necks', and steeply curved funnels of the final sculpture (Fig 5).


2. (above) Prototype.


3. (right) Wax models.

Arup *Realtime*

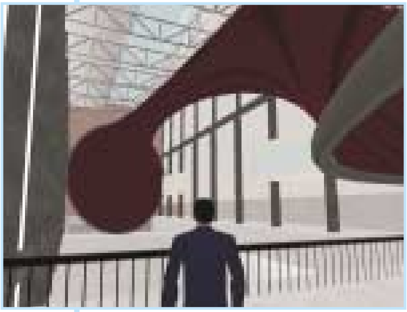
a.

a-d Frames from the Marsyas *Realtime* ‘walk through’ sequence.

b.

c.

d.



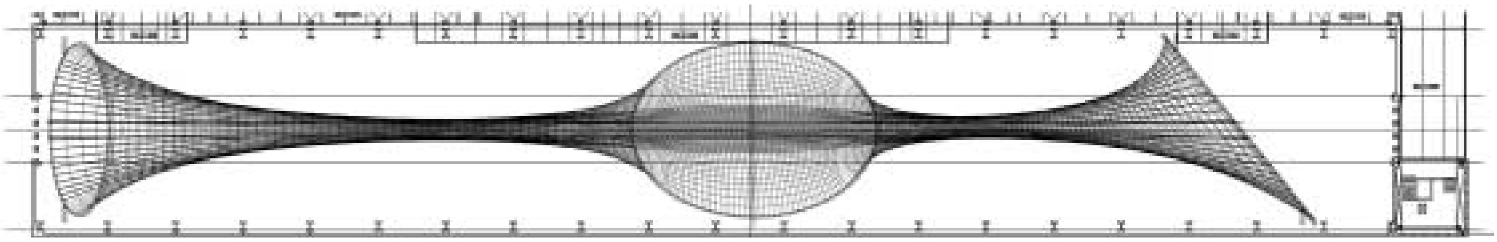
Realtime is a novel capability being developed by Arup to allow non-3D specialists to visualize, interact, and evaluate 3D models of proposed designs or 3D worlds in real time, in an easy, intuitive way on current Arup specification hardware and without the need for expensive visualization or CAD software.

In the collaboration with Anish Kapoor on Marsyas, the novel technique allowed the artist and design team to quickly and effectively visualize and evaluate the complex sculptural forms being developed on a nearly daily basis. Moreover, it allowed them to ‘experience’ the proposed designs in the context of their final surroundings.

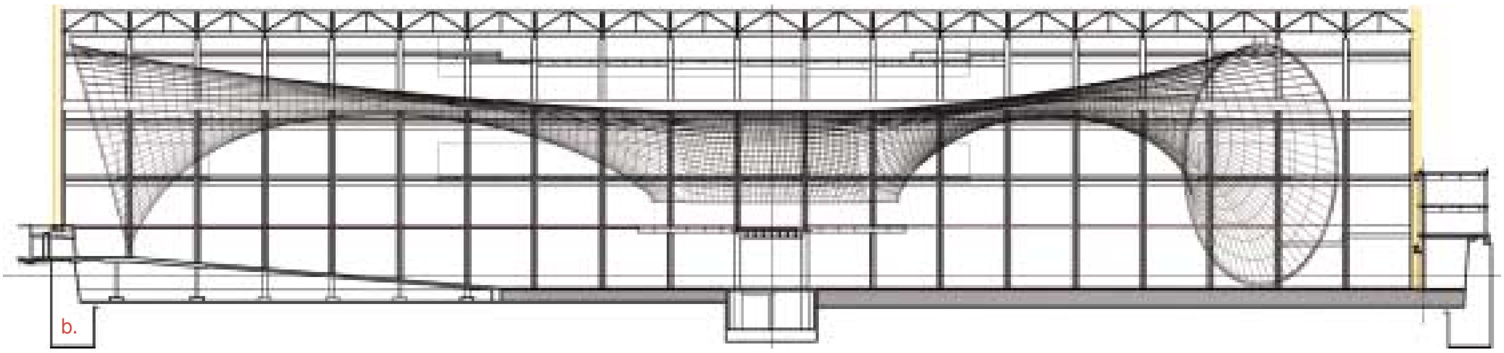
A 3D model of the Turbine Hall was created in AutoCAD from existing 2D CAD drawings and subsequently imported into 3D *Studio Max* for a basic makeover of textures to match the real building. The iterative process involved:
(1) importing sculptural forms created in *Rhino* or *Form-found* in Fabwin/GSA into the Turbine Hall 3D model;
(2) exporting the *Max* scene to the *Realtime* engine;
(3) running the ‘walk through’ to assess the design in an accurate and realistic setting.

Realtime uses cutting-edge 3D graphics technology developed by the computer games industry, allowing the navigation and interaction of large, high polygon count, 3D worlds in real time requiring only a standard specification PC with a £100 ($/euro150) worth of 3D graphics card. Also, *Realtime* software and the 3D world files can be burned onto a CD and distributed to internal and external parties without the risk of 3D design content being copied or edited.

The *Realtime* development project, now funded by Arup’s Innovation Fund, is currently under way to provide *Realtime* technology and services to the rest of Arup as well as external clients.

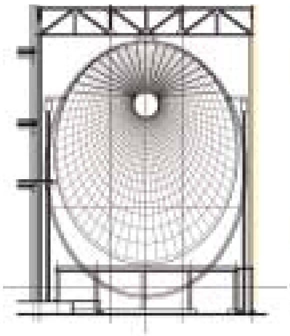


a.

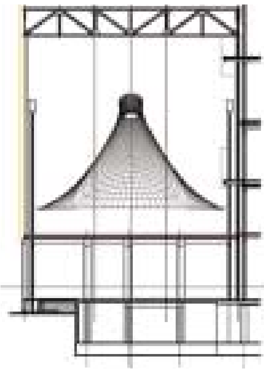


b.

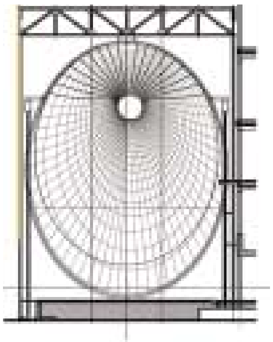
c.



d.



e.



4 Plan (a), elevation (b), and west end, central, and east end sections (c-e) of the final design within the Turbine Hall.

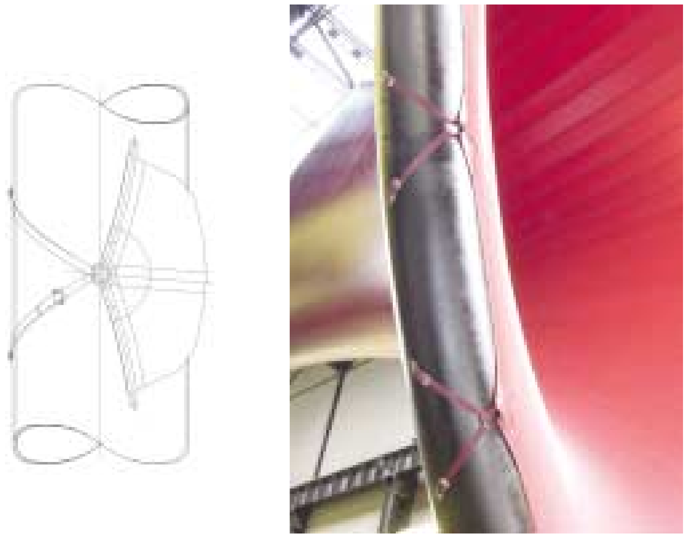
5. FABWIN stress plot.

When the real fabric structure was eventually cut from panels of fabric, prestress was added by cutting each panel too small, essentially shrinking the membrane so that when it stretched to its correct shape it had the correct prestress and remained stable and taut. The enormous 140m span, combined with the particularly shallow catenary and narrowness of the sculpture's 'back', resulted in extremely large membrane prestresses along the top of the structure. To limit the potential for wrinkling between adjacent fabric panels that this large prestress range could cause, 19 high strength polyester belts were introduced along the back of the structure to help share the load.

PVC-coated polyester membrane was the natural choice of material because of its strength, robustness, cost, and ability to be coloured to the artist's particular requirements. The form's extreme shape meant that the material's behaviour had to be predicted as accurately as possible. This led to the selection of a specific 1.8m wide PVC Type II fabric manufactured in France, woven and coated under tension, to provide consistent and predictable properties. Some 5km of it were needed.

Connection details were integral to the process of introducing prestress into the membrane - and had to be aesthetically acceptable to the artist.

Details able to deal with the tolerances of working over such a large span, and with an ever-changing angle of incidence with the steel rings, were developed in conjunction with Kapoor and the membrane contractor. The splayed belt detail that emerged minimized the use of metal parts and maximized the flexibility to allow for standardization across all connections (Fig 6).



6. Membrane connection details.

The steel support structure

A particular ambition for this structure - the two end rings and their connection into the existing building - was that it effectively became part of the building fabric. With its 'language' of simple industrial components, the membrane form had to appear wedged or jammed into the Turbine Hall. Aside from these artistic ambitions, the steelwork also had to resist very large tension forces from the 140m span membrane structure.

7. Commencing erection of east steel ring.

The final solution was simple, utilising as much of the existing building structure as possible and so reducing construction costs, but much work was put into engineering the details to be unobtrusive and easy to erect. The existing gantry crane support structure (designed to support two 50 tonne cranes) was clearly a candidate to support some of the loads that would be generated via the tension membrane both vertically and horizontally.

As built, each end ring is of 508mm diameter circular hollow sections (CHS) that span effectively between five points, transferring all the tension applied by the membrane structure to these points primarily via bending, with some torsion due to the eccentricity of the membrane support system.

In turn these five points are resisted via compression struts spanning between the similar five points on the ring at the other end of the Hall. At three of the five points the existing building provided these struts - the two crane rail girders at each side and the concrete slab at the base. At the other two points, two lines of 168mm CHS were inserted into the plane of the roof. Despite compression loads in excess of 15 tonnes in each of the lines, relatively slender sections could be used as they are designed to be restrained by the existing trussed roof structure against buckling.

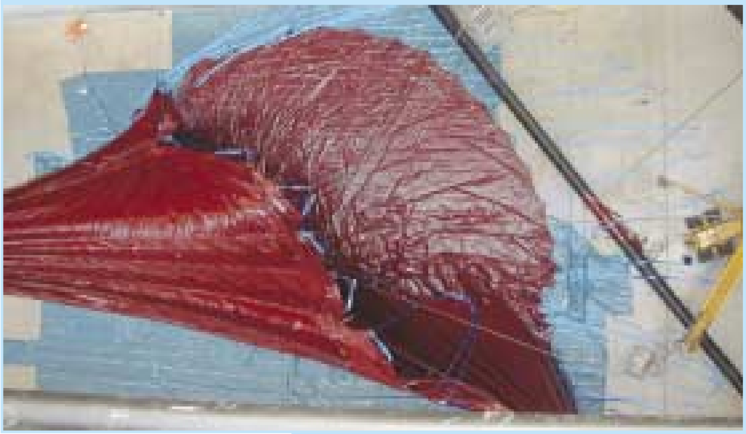
The self-weight vertical load of the membrane and the steel itself - some 45 tonnes - is resisted by only the support points attached to the crane rail girders, thus avoiding overstress of the existing Turbine Hall floor slabs.

The steel rings were designed in transportable sections and bolted together on site using internal end plates. As well as allowing for easier erection, the bolted connections also enable the sculpture to be de-installed - an integral part of the design requirements.

8. Raising membrane at east end.

9. Abseiler securing connection

10. Membrane at east end viewed from above prior to erection.



11. Fabric at east end.

13. Membrane close to final position.

12. Membrane prior to stretching around central ring.

'It is jammed into the building so as to not allow anything but a partial view. The work must retain its mystery and never reveal its plan': Anish Kapoor

Fabrication

Arup advised the Tate to make a direct appointment with the specialist contractor Hightex because of the shortage of time. A price was agreed very promptly and Hightex became an integral part of the team. There was full co-operation and the team did everything necessary to make the project happen. Hightex employed a sub-contractor, Tensys, in Bath, to produce the cutting patterns for the membrane - bringing to bear their own considerable skills to solve some tricky issues. In retrospect that was an important decision. After Arup had finalized the surface form, the 3D geometry data was sent to Tensys. Their complex digital process involved slicing the form into panels, shrinking them according to prestress, and finally squashing them flat so that they could be cut from lengths of fabric off the roll. The patterns were then sent to for printing at full size in Belgium prior to arriving at the workshop in Hungary for fabrication by Hightex. Here the panels were cut and welded together along seam lines, using a high frequency welding technique - somewhat like tailoring but on a giant scale.

The final arrangement of panels and seams attempts to balance the aesthetic need for the sculpture to be a monolithic piece, with seam lines flowing unbroken along the entire length, with the practical constraints of the 1.8m roll width and the difficulties in manhandling and guaranteeing the workmanship on such a large piece of material.

The resulting seam arrangement allowed the monolithic piece to be fabricated initially in three sections and then joined, producing the ‘petal’ effect seen at each end of the suspended ring (Figs 14 & 15).

The steel rings were curved to their required radii via a process called induction bending. CHS sections are passed through an electric induction coil that generates an area of very local high heat (about 50mm wide) via electrical currents induced through the coil’s powerful magnetic field. The steel sections are clamped at their leading end to a pivoted radius arm that is adjusted to controlled radii, centimetre by centimetre, until the required geometry is achieved. Once bent to the correct radii, the six segments of each ring were cut to length and end plates were cut out, drilled and welded in place. All the ring connections were trial-assembled in the fabricator’s yard to ensure perfect fit-up before delivery to site.

Given the tight programme a just-in-time fabrication schedule was adopted. As the first pieces were delivered to site for assembly, the final pieces of the central ring were leaving the induction bending works for fabrication. Simultaneously the final seams were being welded on the membrane prior to crating up for transportation from Hungary.

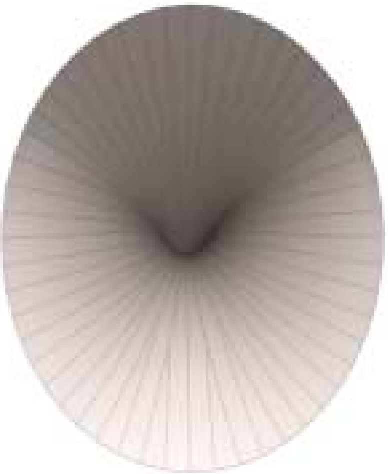
Installation

To meet the opening date deadline and to minimize disruption to the operation of Tate Modern, less than a month was available for the complete installation. The entire Turbine Hall was closed to the public for the installation period.

With only two weeks programmed for the steelwork erection, followed by a further two weeks to install the membrane, meeting the launch party deadline proved to be a real race against the clock. For Tate Modern late delivery was not an option: invitations had already been sent out, champagne and canapés ordered, airline tickets paid for. Sheer dedicated hard work from everyone involved delivered the project on time. The whole team bought into an effective ‘no-blame’ culture, where instant problem-solving and a co-ordinated team response enabled effective trouble-shooting of any hitches during erection.

Given this commitment, the team finished a ‘comfortable’ two hours before the first guest arrived!

14. Seam arrangement within central ring.



15. Seam arrangement at west end.

16: Marsyas complete, the west end viewed from the central bridge.

17. Marsyas complete, viewed from the east end of the Turbine Hall.

Project facts

- Fabric membrane: PVC-coated polyester woven type 2 fabric, manufactured and coloured in France
- Fabric colour: unique and specially developed for Marsyas
- Fabric area: approximately 3500m^2
- Structural span: approximately 140m
- Form fabrication: from precisely derived patterns seamed together in Hungary
- Maximum fabric tension: approximately 1.5 tonnes/m
- Total length of fabric strip: approximately 3km
- Steel ring construction: induction-bent 508mm diameter circular hollow sections
- Quantity of steel: approximately 50 tonnes
- Fabrication duration: approximately 10 weeks
- Installation duration: four weeks
- The installation's title is from Greek mythology: Marsyas was a satyr who, having lost a musical contest with Apollo, was flayed alive by the god.

Conclusion

Marsyas showed what can be achieved when a collection of bright, imaginative, and enthusiastic people are brought together and given the opportunity to create something special. Already the Tate has published a superbly illustrated book about the design, construction, and installation of Marsyas[2], and two films have been made. One, focusing primarily on Anish Kapoor, was produced by Illuminations for BBC4's EYE series, whilst 'Engineering Marsyas' was made for Arup by Steph Harris.

For further information on Thermojet 3D prototyping, contact Martin Self (+44 (0)20 7755 2093; martin.self@arup.com), and on Arup *Realtime* virtual reality software and Arup Fabwin software contact Tristan Simmonds (+44 (0)20 7755 3543; tristan.simmonds@arup.com).

References

(1) HIRST, John, et al. Tate Modern. *The Arup Journal, 35*(3), pp3-11, 3/2000 (Millennium Issue 4).

(2) THE TATE. Anish Kapoor: Marsyas. Tate Gallery, 2003.

'To tackle the verticality of the space one has to paradoxically take on its entire length': Anish Kapoor

Credits

Client:
Tate Modern

Artist:
Anish Kapoor

Structural engineer:
Arup Cecil Balmond, Chris Carroll, Brian Forster, Ray Ingles, Sharon Nolan, Martin Self, Tristan Simmonds, Charles Walker

Membrane contractor:
Hightex

Patterning and compensation analysis:
Tensys

Steelwork fabricator:
SHStructures.

Illustrations:
1, 3-16: Arup
2: Studio Kapoor
17: Dennis Gilbert
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