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The Making of HOWL by Anish Kapoor: a Fitting Inflated Sculpture

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Abstract. Contemporary art is often abstract and enigmatic. In many cases, it is not meant to be understood, but rather is experienced. Contemporary artists employ symbolic, sometimes, instinctive associations to certain colours, shapes and patterns to instigate an emotional response from the viewer. To achieve this, their works can be purposefully distanced from realism and be devoid of superfluous details. However, this minimalistic approach does not always apply to the scale of the artworks. One of the most influential contemporary artists, Anish Kapoor, is famous for his monumental installations that blur the boundaries between architecture and sculpture. His latest work, entitled “HOWL”, is a site-specific inflated fabric form installed in the Rotunda of the Pinakothek der Moderne, Munich, Germany in September 2020 to mark the 18-year anniversary of the museum opening. At 21.5m in diameter and 14.3m in depth, the burgundy-coloured ellipsoidal form is the largest exhibit that has ever been displayed in the museum. It fills the Rotunda and is seemingly squeezed between its columns extending naturally into the spaces between them and hanging at the height of 2.75m over the ground. This creates a powerful visual and formative interaction between the art object and the building, which has been a focal design intention.

The enormous pneumatic sculpture had to be tailored perfectly to the building to convey this effect. Any deviations from the desired form could lead to wrinkles, overstressed or slack fabric areas and loss of symmetry, which would impact the fine artwork aesthetically and could even prevent its installation. Tensys have been tasked to realise the artist’s vision of HOWL, undertaking fabric analysis and patterning. This paper presents the methods used to address the engineering challenges in this project and describes the process of modelling of the inflated structure using a combination of FEA and parametric CAD tools.

1 INTRODUCTION

HOWL is the latest in a series of Anish Kapoor’s membrane structures. Over the past 20 years, Tensys have also worked as a specialist engineering consultant in a number of Kapoor’s previous projects involving the use structural fabrics. Some notable examples of these projects are shown in figure 1. One of the main advantages of application of membrane materials in architectural projects is the possibility of covering large spans and creating large enclosed spaces with reduced- or, in the case of pneumatic structures, no need for rigid internal supports, all whilst maintaining low weight of the structure. The light weight and foldability of the fabric elements greatly simplify their transportation and installation compared to traditional rigid frame structures. This is particularly beneficial for temporary and mobile structures, such as Anish Kapoor's fabric sculptures.

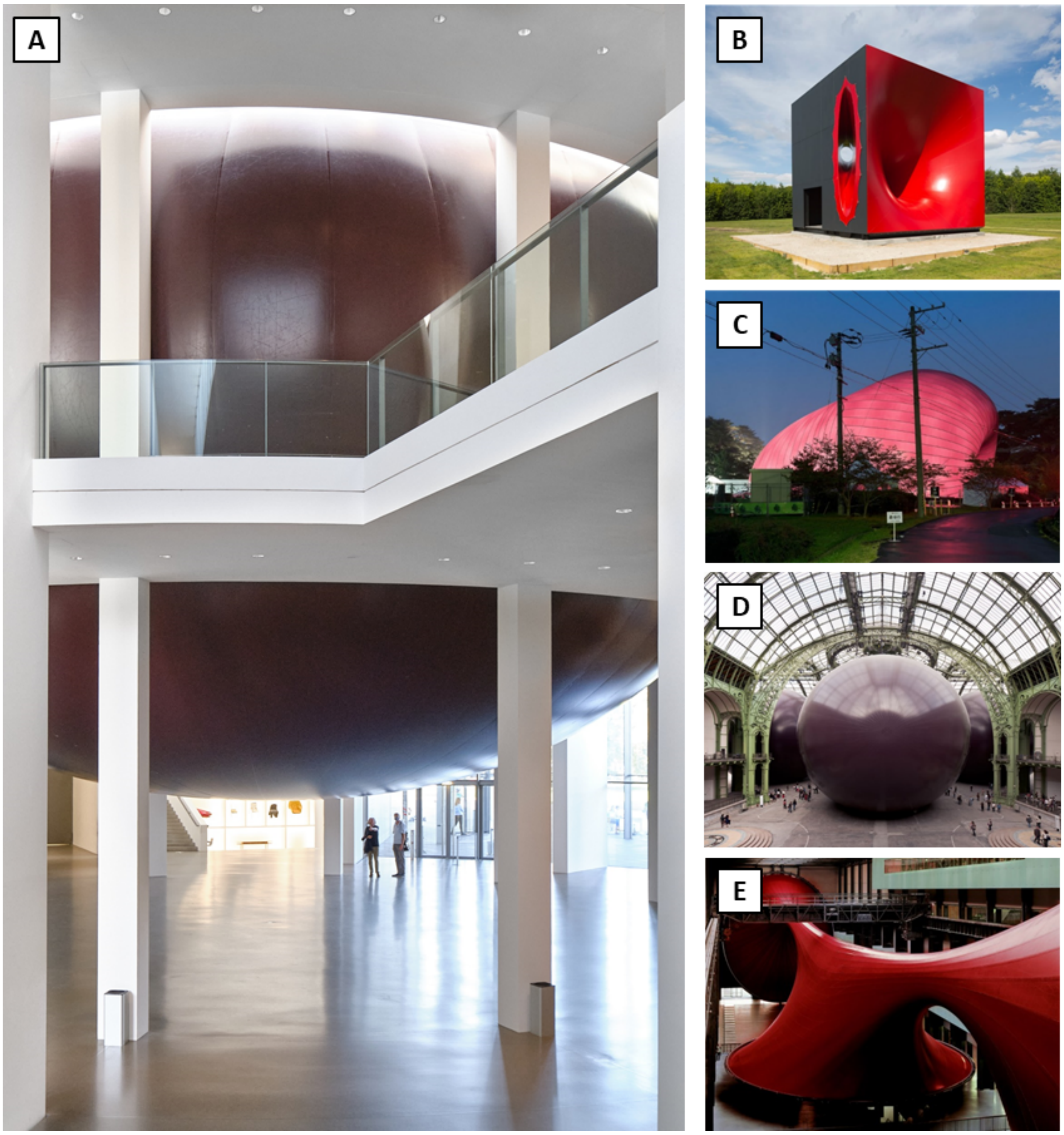


Figure 1: HOWL (A) and examples of previous fabric structures from Anish Kapoor: B – Sectional Body preparing for Monadic Singularity, Chateau de Versailles, Paris (2015); C – Ark Nova mobile inflatable concert hall, Japan (2013); D – Leviathan, Grand Palais, París, France (2011); E – Marsyas, Tate Modern, London, UK (2003). Images courtesy of Anish Kapoor[1]

In contrast to a traditional building envelope, comprised of a collection of rigid elements that define its shape, a fabric skin is self-formed to achieve equilibrium of the internal tensile stresses in the given system of boundary conditions, pre-determined by the designer.[2] The geometry of a prestressed membrane's surface is continuous and smooth between the external supports, cables and other elements that are in contact with it. This enables the designers to achieve a minimalistic look of fabric structures, which reflects their efficiency as a structural system. Positive internal pressure in pneumatic structures produces synclastic curvature of the surface, giving them a very organic appearance that is characteristic for many Kapoor's works, including HOWL.

A key aspect of the HOWL project from both engineering and artistic perspectives is that it takes the idea of formative interaction between the structure and the site to a new level - the sculpture is in contact and is physically constrained by the columns of the Rotunda of the Pinakothek der Moderne. The form stays elevated above the ground at the height of 2.75m (see figure 2), and there are no cables or other types of supports above or below it. Although this purposefully creates an impression that the ellipsoidal object is squeezed between the columns, the area of the contact is small, as if suggesting that the object is almost weightless, when in reality its total mass is close to 1000kg. At the same time, the form retains its pure organic shape and crease- and wrinkle-free smooth surface even at the columns.

It would not be possible to achieve the above if the unconstrained shape of the inflated sculpture was in fact a uniform ellipsoid. This would result in large areas of slack wrinkled fabric around the locations where the sculpture would be pressed against the columns. Instead, the fabric form had to be pre-cambered such that its inflated shape would closely match the final petalled shape of the sculpture, even if the columns were not there. This approach allowed minimising the horizontal forces exerted by the inflated form onto the columns. Yet, a small 0.6m high area of contact between the inflated form and the columns was maintained which enabled suspending the sculpture and, at the same time, concealing the hanger points. The next section describes the process of finding the shape that meets these requirements.

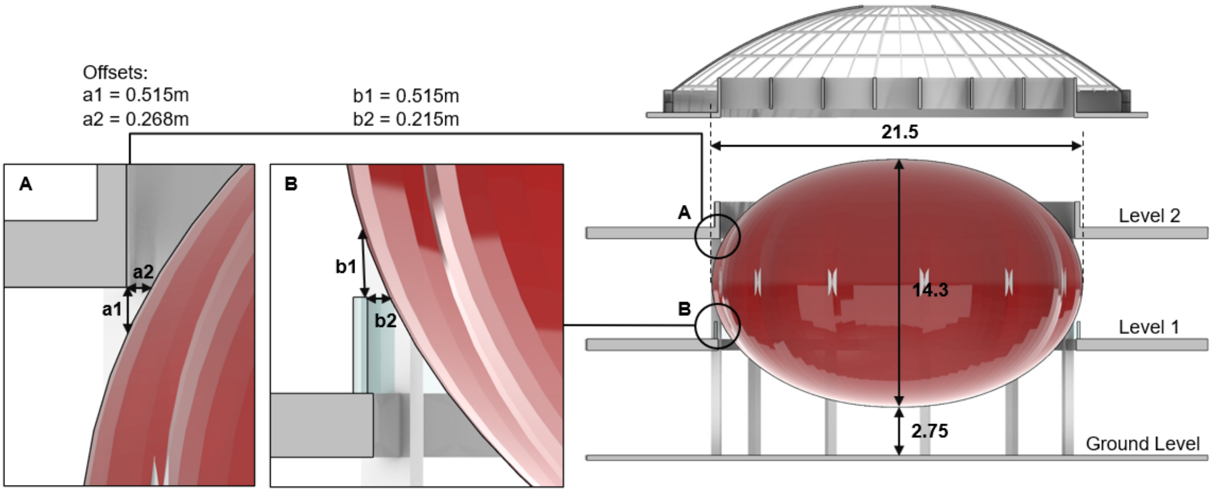


Figure 2: Elevation section through the middle of the Rotunda model demonstrating the shape and dimensions of HOWL and the offsets between the sculpture and Level 2 ceiling (A) and glass balustrade on Level 1 (B).

2 FORM-FINDING

HOWL can be observed up-close from all three floors of the Rotunda, and the whole sculpture is visible from outside of the gallery through the glass façade. It is exposed to the visitors' view from every side and from above and below. To match the artist's vision of the sculpture and meet the level of refinement of the form, surface and symmetry that is fitting for a fine artwork, in spite of its monumental size and contact with the building, required a high level of accuracy at every stage of the modelling and production processes – from prediction of the inflated shape and distribution of fabric stresses, to specification of valid compensation values for patterning, to optimised fabrication and installation.

Tensys employ in-house FEA software suite inTENS for modelling of tensile structures. The software is built on the platform of a Dynamic Relaxation (DR) solver, developed by the founder of the company Dr David Wakefield. The DR numerical method enables determining a steady state solution for geometrically linear and non-linear structural systems modelled as a series of nodes, which are assigned artificial lumped masses and are interconnected by discrete finite elements representing membrane and cable, strut, or beam components. The solution is found by dampening out the load-induced oscillations of the nodes in a sequence of incremental time steps (a.k.a. iterations). The nodal residual forces are recomputed and node coordinates (i.e. form changes) updated at each iteration until the analysis converges to a balanced state of the model.[3,4] The software features an extensive and continuously expanding list of advanced modelling capabilities and tools for analysis and patterning of membrane structures.

A standard procedure for inTENS analysis usually includes 3 stages:

1. Topology creation – definition of the FE mesh and linear elements, where only the locations of fixed nodes need to be final;
2. Form-finding, which generates a unique minimal surface of the membrane based on a pre-determined set of constraint- and prestress conditions;
3. Analysis – where the membrane is elasticated (assigned orthotropic stiffness properties), and the deflected shape and stress state are computed for the applied load cases starting from the form-found geometry and prestress.

In certain cases, a complex prestress state may be required to obtain a specific geometry using the DR form-finding, or, sometimes, such a state may not exist. Pneumatic structures with uneven surface curvature, such as HOWL, are often impractical to replicate using the DR form-finding. Instead, if the required form is known, it can be matched by adjusting the topology of the model and using it as a starting geometry for the analyses. However, the use of such manually imposed starting geometry may result in sub-optimal distribution of stresses and unwanted deformations of the loaded model. Therefore, iterative adjustments of the topology may be required to obtain the desired shape and stress state. Due to the complex surface shape of HOWL, a parametric modelling script (shown in Figure 3) was created in Grasshopper (GH) to provide a convenient and efficient method for adjustment and generation of the model topology.

The GH script is based on the ability to control the geometry of a set of reference curves (figure 4a), used to generate a lofted 3D surface. The main control parameters in the script include the height, maximum diameter and vertical position of the form, the horizontal tangent angle between the surface of the lobes and column contact planes, radial offsets of the reference curves from the columns, fillet radii between the curve components and the number and distribution of the curves. An accurate 3D model of the site was produced in Rhino and used in conjunction with the GH script for definition of the column constraint planes, measurement of offsets between the form and building components, such as the glass balustrade on level 1, and for 3D visualisations of the sculpture within the gallery. At early stages of the project, these visualisations were used by Anish Kapoor as one of the means to assess different design options for the form. In the later stages, the visualisations were employed to select the preferred arrangement of seams and study the effects of fabric colour and translucency on the appearance of the sculpture (figure 4e).

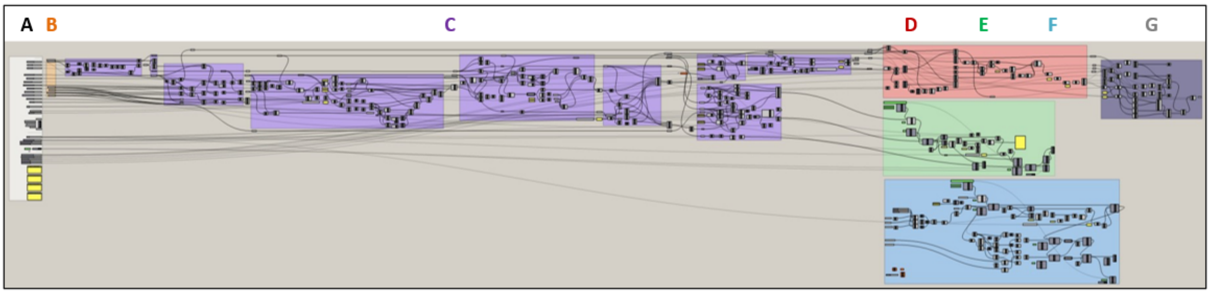


Figure 3: Tensys GH script for parametric generation of 3D surface model and the initial topology for the HOWL project. A – Control panel for adjustment of model parameters, prevew and export of the inTENS topology; B – Imported model of the site; C – Generation of the reference curves; D – Generation of lofted surface for visualisations; E – inTENS topology generation using Tensys Rhino Tools Plugin components; F – Generation of inTENS patterning model topology from an imported analysis shape; G – Generation of seam lines for visualisations.

Based on the building survey data, the deviation of the Rotunda columns from the perfect radial symmetry is negligible. Owing to this, the model was built with 12 identical lobes, meaning that the reference curves did not need to be adjusted for each lobe individually. Each of the 23 curves per lobe were subdivided into 98 segments and imported into inTENS FE topology model in GH using a set of custom components from the Tensys Rhino Tools plugin. The FE mesh (figure 4b) was defined based on the nodes at the ends of the curve segments with circular cap regions at the apex and base. The full 360-degree model was analysed to simplify fixity conditions. The parametrically generated topology model was used as a starting geometry for the initial analyses, where the membrane was assigned typical PVC type II fabric stiffness properties and the inflation of the shape was not constrained by the column contact.

The initial analyses with a range of inflation pressures and repeatedly adjusted starting geometry have revealed challenges in simultaneously matching the required inflated form and achieving a stress state with no destressed or overstressed membrane areas. The inflation of the form typically resulted in slack regions near the middle of the lobes and at the columns near the equator. To address this, a preliminary inflation stage was added, where the first inflated shape was converted into a new starting (deflated) geometry to be reinflated (steps 4 to 5 in figure 5). This provided a substantially improved stress state of the inflated model, and, after several incremental changes to the initial parametrically generated topology, it was possible to obtain an inflated model (at 0.5kPa inflation pressure) that meets both the shape and stress requirements (see the next section for more details on further steps in figure 5).

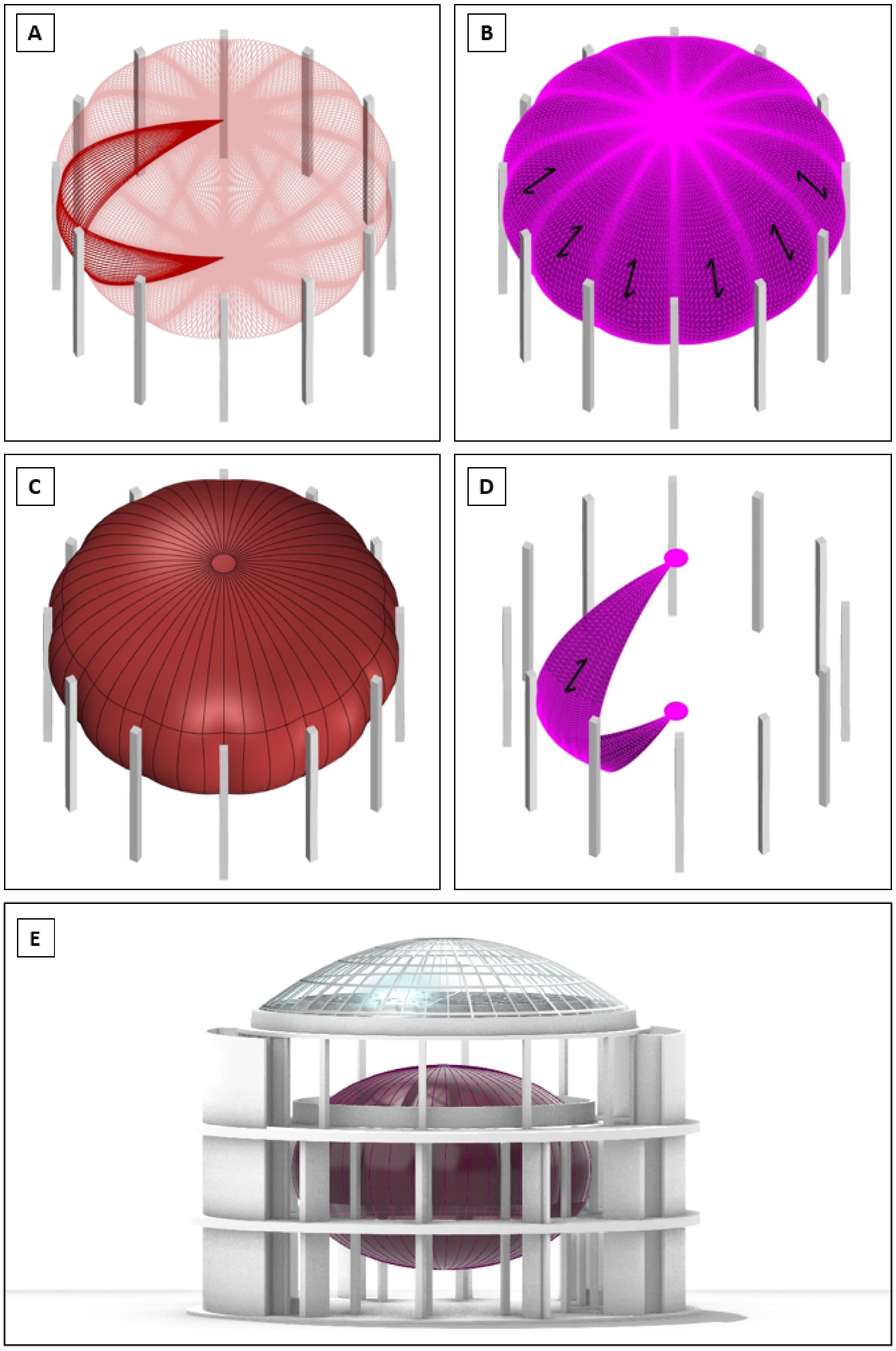


Figure 4: Examples of output Rhino- and inTENS FE models, generated in the GH script. A – Parametrically controlled reference curves; B – Initial topology for the analyses; C – Visualisation of the seam arrangement; D – Patterning geometry; E – Visualisation of the sculpture in the gallery.

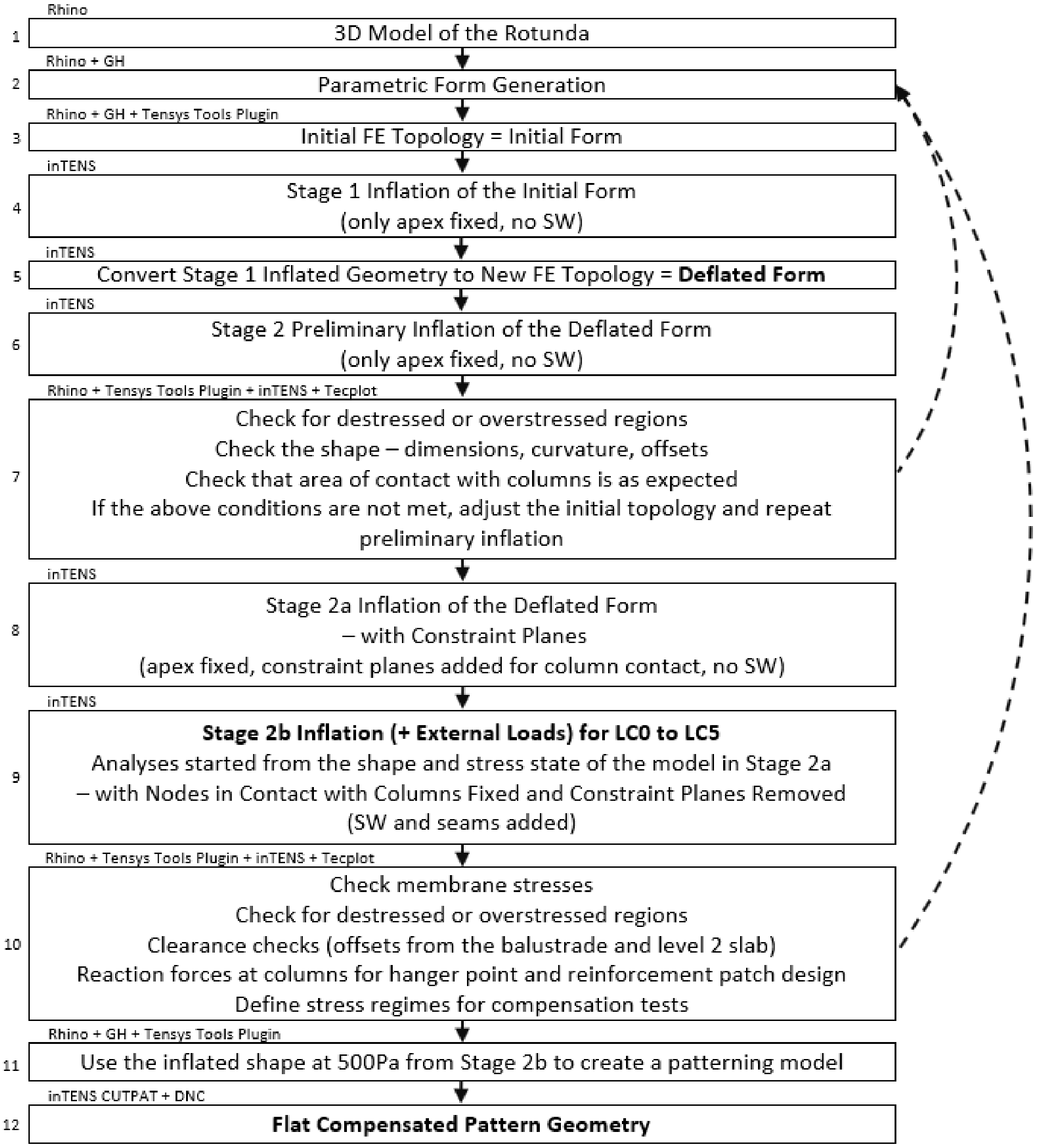


Figure 5: Summary of the modelling process for the HOWL sculpture.

3 ANALYSIS

Upon finding the combination of deflated form and inflation pressure that enabled the model to satisfy the requirements in the unconstrained inflated state (step 7 in figure 5), this form needed to be reanalysed with the correct constraint conditions, i.e. considering its contact with the columns. This was necessary to allow analysing applied load cases and checking the effects of the changes in the constraint conditions on the shape, membrane stresses and reaction forces at the columns in the inflation only LC0 case (step 10 in figure 5).

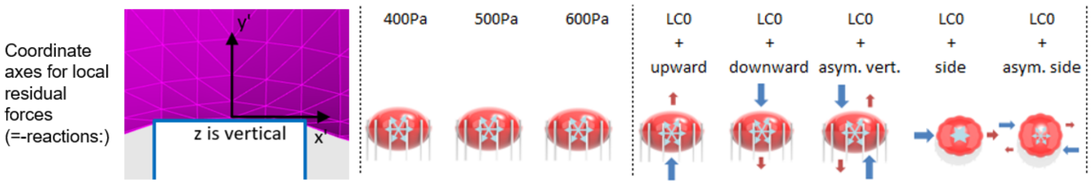
The analyses with the updated constraint conditions were conducted in two stages. In the first stage (step 8 in figure 5), constraint planes (local contact) were introduced at the contact surface of each column and applied for the membrane nodes in front of the columns. At this stage, the vertical movement of the shape was constrained by maintaining the fixity of the apex in z-direction. This stage allowed identifying the nodes of the inflated model which are in contact with the column. In the second stage (step 9 in figure 5), these nodes were fully fixed at their positions from the previous stage and the form was reinflated from the analysis state of the previous stage (shape and stresses). This process was repeated for three LC0 cases with different inflation pressures: 400Pa, 500Pa and 600Pa.

It was originally expected that there would not be notable changes between the inflated shapes from the two stages of the analyses; however, in practice, the replacement of the local contact planes with fixation of the contacting membrane nodes facilitated improved convergence of the analysis solution in the second stage. This manifested itself in a more accurate prediction of the inflated shape, which expanded slightly more vertically. This effect may be explained by the elimination of contact-induced vibrations of the contacting nodes after they are fixed.

Another interesting observation was made when examining the influence of inflation pressure on the unconstrained and constrained inflated form. The ellipsoidal form does not expand uniformly when the inflation pressure is increased. Instead, it tends to expand vertically and, depending on the starting shape, may shrink horizontally (transforming into a more spherical shape). Therefore, somewhat counterintuitively, increasing the pressure in the HOWL sculpture would result in a reduction of its outer diameter, which would also reduce the extent to which the shape protrudes between the columns. This tendency can also lead to loss of hoop stress at the equator of an inflated ellipsoidal fabric form.

It was found that 500Pa inflation pressure provides a good balance between ensuring biaxial stressing of the fabric and maintaining sufficient firmness of the surface, whilst matching the required inflated shape accurately. Hence, the applied load cases were analysed with this recommended inflation pressure, each starting from the stress state and shape of the model from the inflation only case. The applied analysis cases included uniform uplift, uniform downward pressure, overturning vertical pressure, side pressure and asymmetric (twisting) side pressure (LC1 to LC5 in table 1), each combined with 0.5kPa inflation and fabric self-weight of 815g/m^2 from LC0.

These analyses were aimed to account for possible loading from draft wind pressures inside the gallery. Wind pressures for each load case were computed as a product of the site-specific peak velocity pressure with a 5 year return period (0.4kN/m2, calculated in accordance to DIN EN 1991-1-4/NA Germany: 2010-2012)[5] and pressure coefficients, which were based on the absolute value of the larger internal pressure coefficient recommended for enclosed buildings with uniformly distributed openings (-0.3) in DIN EN 1991-1-4 7.2.9 (6) Note 2[5]. +0.3 pressure coefficient was used for membrane areas on windward side and -0.15 suction coefficient was applied for the opposite side of the form (except asymmetric load cases, where equal alternated pairs of pressures acting in opposite directions were applied on each side of the form). Thus, a conservative assumption was made that the pressure and suction are acting in the same direction in each case resulting in the worst-case loading. The maximum fabric stresses and reaction forces at the columns from the analyses are summarized in table 1. The stress plots for LC0 and LC5, the latter of which results in the maximum membrane stresses, are shown in figure 6.



	Inflation only:			Interior Load Cases:				
	LC0_400	LC0_500	LC0_600	LC1	LC2	LC3	LC4	LC5
Maximum membrane stresses:								
Maximum Warp Stress (kN/m)	6.63	8.42	10.21	9.23	9.49	8.94	8.34	**10.70**
Maximum Fill Stress (kN/m)	5.67	7.13	8.61	7.82	8.01	7.51	6.95	**10.97**
Maximum residual forces at columns (= -reaction forces) in each load case using LOCAL X'Y'Z'								
Rx' max +ve (kN):	0.01	0.02	0.02	0.01	0.01	2.29	5.77	2.70
Rx' max -ve (kN):	-0.02		-0.02	-0.03	-0.03	-2.31	-5.76	-1.74
Ry' max +ve (away from the column) (kN):						0.11	0.99	0.08
Ry' max -ve (towards column) (kN):	-0.23	-0.30	-0.38	-0.27	-0.20	-0.75	-1.44	-0.80
Rz' max +ve (up) (kN):				4.52		1.98		
Rz' max -ve (down) (kN):	-0.76	-0.78	-0.77		-6.01	-3.64	-0.80	-0.79
Total maximum reaction forces (kN)	0.80	0.83	**0.85**	4.53	**6.01**	4.33	5.84	2.85

Table 1: Summary of maximum reaction forces and stresses in the analyses.

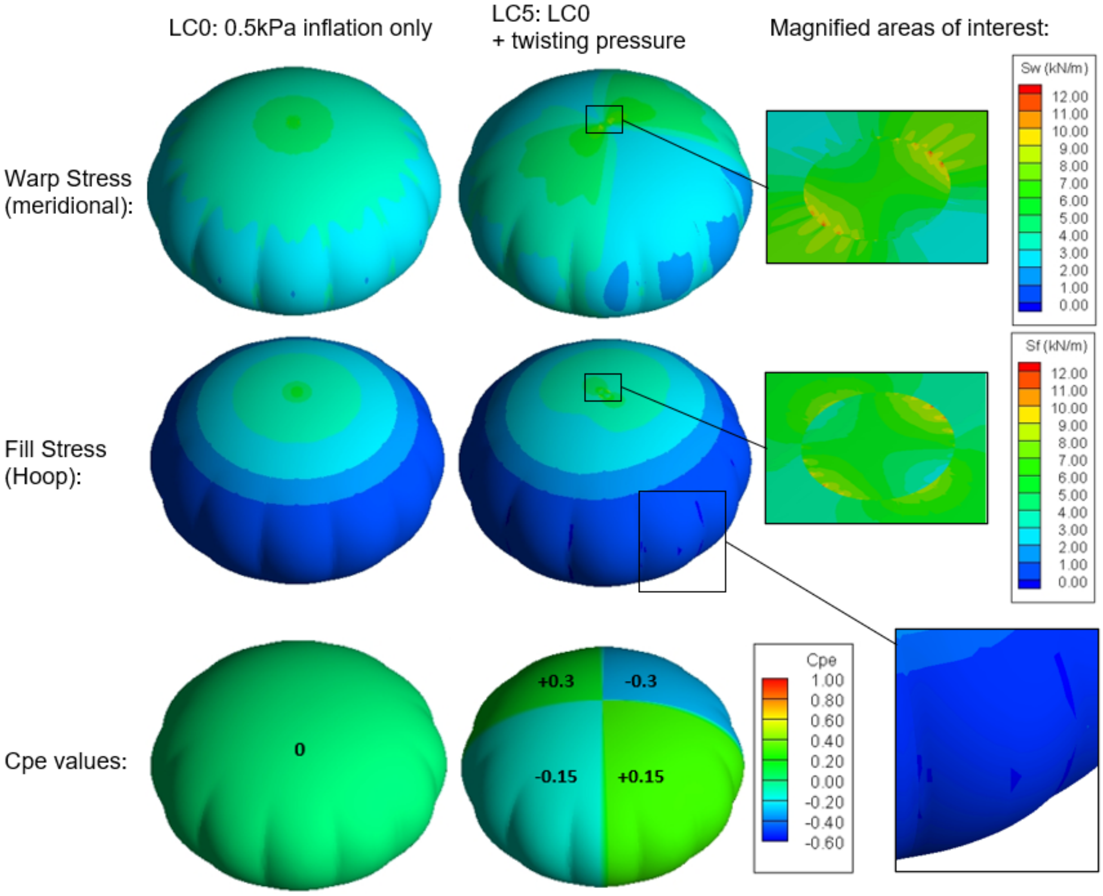


Figure 6: Stress plots and Cpe values for LC0 and LC5.

As seen from figure 6, a state of biaxial stress is maintained over the entire surface of the inflated form in LC0 with 500Pa pressure, albeit with reduced fill stress around the equator. The loss of stress in the hoop direction under applied loading over small areas of fabric, such as in LC5, was deemed acceptable. No areas unstressed in both directions were observed in any of the load cases.

Given the maximum predicted membrane stress of ~11kN/m (concentrated at the caps), a PVC type I fabric with UTS>55kN/m (FOS 5.0) was recommended as the choice of material for the HOWL sculpture. However, this was conditional on the use of 1.5m diameter circular panels, at apex and base of the form. These panels were needed to prevent excessive stress concentrations resulting from the warp direction loads being carried along the radially aligned panel layout, to an ever-decreasing circumference at the top and base. The circular panels act to spread the load over a wider membrane area and allow avoiding multiple overlapped radial seams.

The reaction forces at the columns were extracted to enable designing the connection details between the sculpture and the columns. AR Ingenieure in collaboration with ITF developed thin slotted connector plates and fabric reinforcement that are hidden out of sight behind the 0.6m high areas of contact (figures 8b and 8c).

4 PATTERNING

The patterning geometry for HOWL was produced by importing the inflated shape of the model from LC0 back into the GH script, where it was discretised into a new FE mesh, based on the selected ‘4-4-4’ panel arrangement (figures 4c and 4d). This arrangement comprised of four meridionally-oriented panels in the top, middle and bottom parts of each lobe and two circular caps. The horizontal seams were positioned at the middle of level 1 and 2 slabs for concealment, and vertical seams and panel centrelines were on geodesic paths in order to minimise shearing errors[6]. This arrangement of the panels was chosen as it provided an optimal balance between accuracy of the unfolded patterns, efficient use of the fabric roll width and aesthetic considerations. An interesting detail is that, when viewed in plan, the seam arrangement matches the lattice of the roof of the Rotunda.

Flat patterns were generated in inTENS using the compensation strategy shown in figure 7a. The compensations were necessary to account for the strains resulting from crimp removal and deformation of stressed fabric. The compensation values were obtained from 5 biaxial compensation tests with different stress regimes, chosen in accordance with the stresses from analyses at 6 probing locations indicated in figure 7a. Strain values for the compensations were taken from the end of a 6 hour-long final hold period in each test, with the negative compensations eliminated as explained at the bottom of table 2. Different warp and fill compensation values were prescribed for the circular caps to ensure that they remained circular upon inflation of the structure despite different fabric stiffness in the two yarn directions. Small local adjustments (up to 0.076% in warp direction and 0.28% in fill direction) were applied to maintain compatibility between the adjacent fabric panels. Offsets for 40mm wide seams and markings, showing the locations of air inlet and reinforcement patches at the hanger points, were applied in DNC software (figure 7b).

Figure 8 shows the completed inflated structure in the gallery from different angles.

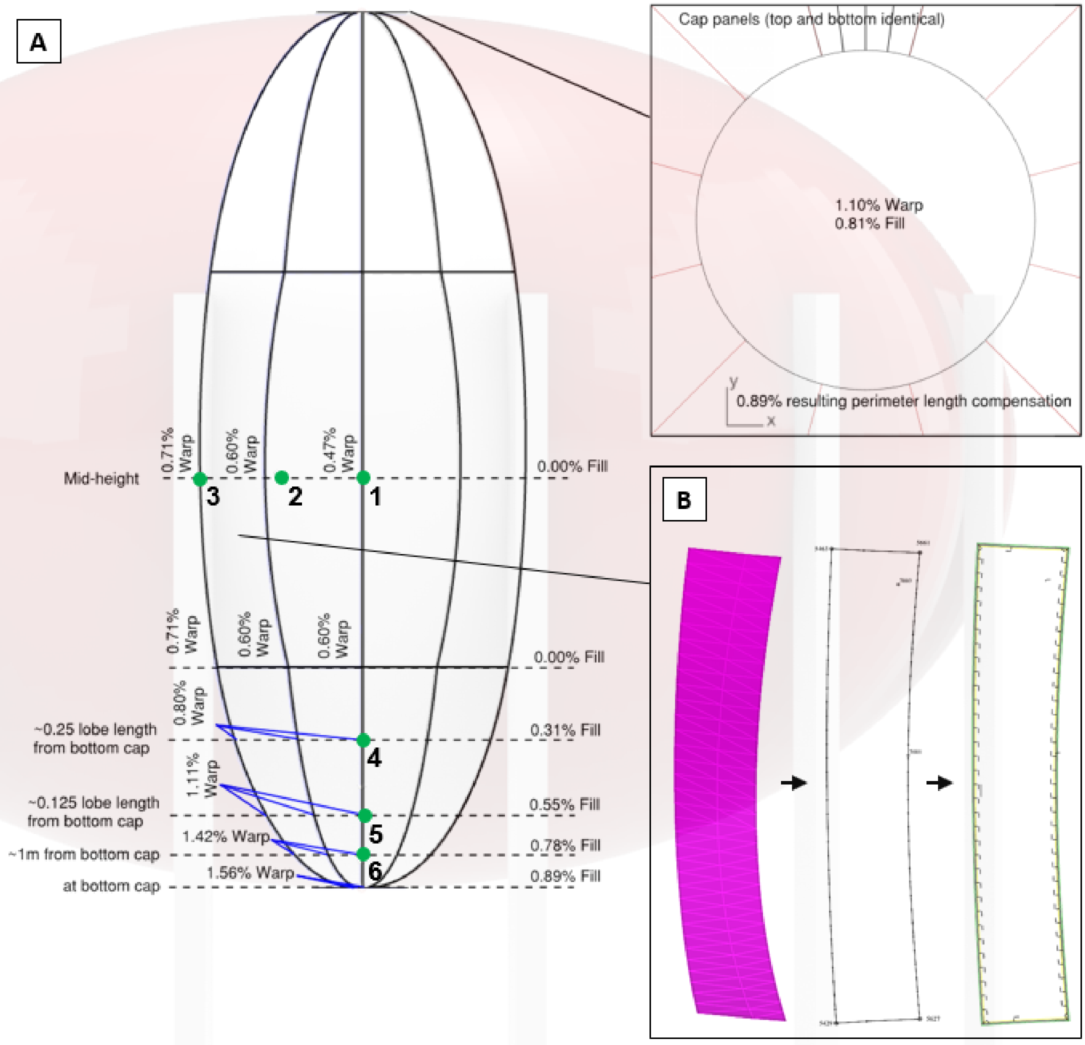
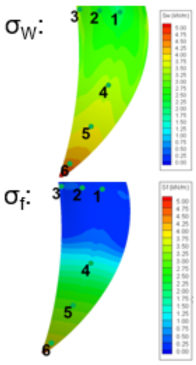


Figure 7: A – Compensation stratigy for the patterns (identical for all lobes). Compensations in regions between the shown locations vary linearly. B – An illustration of the patterning stages – from the curved geometry, to flattened compensated patterns, to the addition of offsets and markings.



	Stresses in compensation tests:				Strains at the end of hold stage		Negative strains eliminated*	
	PS Warp (kN/m)	PS Fill (kN/m)	Max Warp (kN/m)	Max Fill (kN/m)	Warp Strain w1 (%)	Fill Strain f1 (%)	Warp Comp w2 (%)	Fill Comp f2 (%)
Test 1: probe 1	2.0	0.2	3.0	1.0	0.76	-0.59	0.47	0.00
Test 2: probe 4	3.5	2.5	5.1	3.0	0.80	0.31	0.80	0.31
Test 3: probes 1 and 4	3.0	1.0	5.1	1.7	0.97	-0.29	0.83	0.00
Test 4: probe 6	4.7	3.9	8.7	5.3	1.42	0.78	1.42	0.78
Test 5: probe 3	2.7	0.3	5.3	0.5	1.06	-0.70	0.71	0.00

* Strategy for elimination of negative compensations:
If $f1 \geq 0 \Rightarrow w2 = w1$ and $f2 = f1$
Else $w2 = ((w1 - f1) + w1) / 2$ and $f2 = 0$.

Table 2: Summary of stresses applied in the compensation tests and the extracted compensation values.

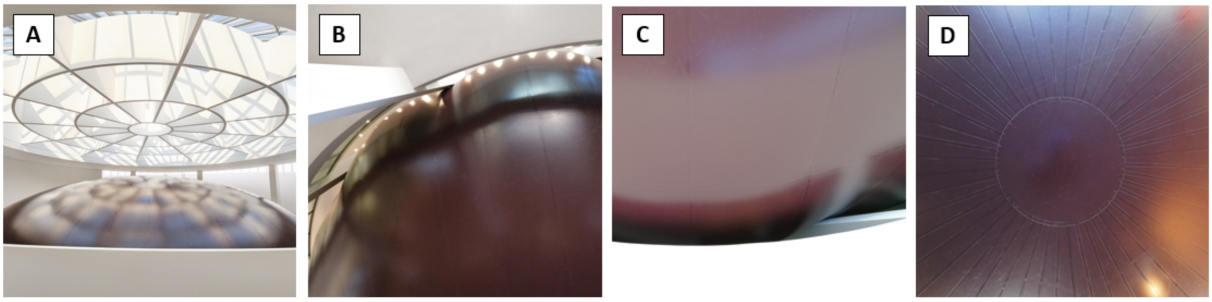


Figure 8: The completed inflated structure viewed from level 2 (A), ground level (B), above one of the twelve protruding lobes (C) and below the base (D). Images courtesy of Anish Kapoor[1]

5 CONCLUSIONS

The successful completion of the HOWL project demonstrates the validity of the methods employed by Tensys for modelling of the structure and generation of the compensated patterns. It was shown that the complex shape of the pneumatic structure can be matched accurately using an iterative process of adjustment of an initial parametrically defined form that is pre-inflated to achieve the required starting deflated geometry. The completed HOWL sculpture has also met the expectations of its creator – Anish Kapoor, who described it as “precise down to a millimetre”[7].

ACKNOWLEDGEMENTS

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