5.4

Soundforms

The design, development and fabrication of a 1:1 scale mobile acoustic performance shell prototype

Paul Bavister [i]

Soundforms is an acoustic shell developed for natural acoustic reinforcement for external ensemble performance. Discussions on the project started in 2007 in conjunction with conductor Mark Stephenson, and a team was established with Jason Flanagan, Paul Bavister of BFLS and Ian Knowles of Arup Acoustics, who collaboratively developed the brief into a full patent for a mobile acoustic performance shell. It was decided that a prototype should be developed prior to commencing commercial production. This was to be sure that the costs of production were feasible, the engineering brief was realistic, the notion of mobility and portability was practical, and of course, that the core acoustic idea could be verified through acoustic tests in performance. A fully working prototype would also enable potential clients to test the concept, and 'kick the tyres'. The ultimate goal of the project was to take music outside of the concert hall with a higher quality of acoustics than was previously available.

Fig 5.4.1 Soundforms: Mobile Acoustic Performance shell

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Portability & Democracy

The history of externalised performance goes back to ancient times, spontaneous performances taking place before any assembly of people large enough to form a willing, or unwilling audience. In some cases this was in front of fixed site, such as a well, and many established theatres have taken their name from the original well that marked the site of the original performances, such as Sadlers Wells. Whilst impromptu performances that took place in front of fixed locations have lead to permanent theatres, economic conditions often prohibited the establishing of a purpose built housing for performance, and have led to travelling performances that would establish themselves temporarily at fairs and other public locations before moving on to new locations. A typical example of this is the Commedia dell'Arte, where players performed on temporary open-air stages, using props instead of scenery. If successful, they were funded primarily by the towns and cities where they played. Extra funds were generated by the passing of a hat amongst the audience, this ensured that the performances were not exclusive, and everyone was able to view free of charge.

Fig 5.4.2 Verona Arena, Boeve, Ervina, 1772

In conjunction with a desire to take performance outside of the theatre is the development of architectural technology that utilizes industrial techniques of construction that allows for rapid deployment and transportation. Developed in the early twentieth century to improve the quality and speed of construction, such buildings by Buckminster Fuller, and Charles and Ray Eames buildings had a new level of flexibility that freed the building from the more traditional constraints of site and permanence.

Existing acoustic conditions

Prior to the development of Soundforms, all exterior acoustic performances took place in fabric tents that protected performers from the weather yet offered no acoustic

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reinforcement on the stage. Musicians use this acoustic reinforcement, or room feedback, to modulate and improve their own performances and take timing cues from other players in the ensemble. Without this, such as a typical tent, the performance suffers, and with it, the experience of the audience. Performance shells exist for internal spaces to make up for architectural inconsistencies in spaces not intended for music performance. These can be flown from fly towers, and use a host building's structure for support. They are not designed for external use. Fixed and permanent external structures do exist for performance, the Hollywood bowl is a classic example, but due to the weight of the components to distribute the sound to an audience, these structures have remained solidly fixed to the ground.

Procurement

Where Soundforms differs from typical architectural projects, is that at the outset there was no client, or direct revenue source for the project in this instance. The design team self-funded the early design- concept phases of the project, enabling further funding to be in place for the development of a 1:1 scale prototype. The early phases of design were intrinsically linked to the development of a working acoustic brief that could be digitally proved to be fulfilled as a proof of concept. The Soundforms team analysed 3 differing typologies of acoustic performance, and developed the product to acoustically optimise each of the conditions. These were a string quartet, a small chamber ensemble, and a full symphony orchestra, each acoustic condition having differing requirements that required their own spatialised solution. Each of these conditions could be defined by a set of acoustic ratios, being the defined distances between reflective surfaces inside the shell. These ratios were then distilled into UK patent application no. 2472238. Once a patent was in place, funding could begin with the aim of developing the finished product for industry testing, and ultimately commercial production.

Brief

The origins of the brief lie in Mark Stephenson's work with Arup Acoustics work in trying to develop a shell for touring use in larger indoor spaces in the UK, that were not originally designed for use by a small touring orchestra. These spaces were usually corporate atria, and exhibition spaces such as galleries. In an effort to control the acoustic, a small portable shell idea was conceived. Whilst the resulting shell was fabricated, and tested with mixed results, and went into a slow period of development, leading to larger scale deployments in sketch form. The shell remained in this state until 2007 when Mark Stephenson discussed the project with BFLS who took on the challenge of developing the basic principles into a reality. Arup Acoustics were again appointed to optimize the shape and the materials for a fully outdoor portable orchestra shell that will be used for the performance of outdoor classic music.

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The core brief items were:

- That the orchestra shell would be optimized to help the projection of sound towards the audience and to provide good performance conditions for the musicians on stage in the context of an outdoor venue;

- The overall dimensions of the orchestra shell would have to be directly proportional to the size of the orchestra;

- The size of the orchestra would be related to event location and repertoire and because of this three standard orchestra sizes would be considered to cover the most likely platform sizes to accommodate the following types of performance / repertoires;

- Romantic era orchestra, based on up to 100 musicians;

- Chamber music orchestra, based on a small group of up to 50 musicians;

- Small ensemble, such as a quartet or quintet.

Development

The early forms of the shell were exercises in practicality, and were developed to test the principles of the brief. The acoustic principles were a core driver, as was the existing stage engineering technology that would have to be applied to the shell. These practicalities were then synthesised into a holistic design. The core idea for the form came from the notion of a seashell that mythically is able to project the sound of the sea to a listener. The form is one of the most beautiful in nature, and perfect match for the acoustic principles of the design, that of a throat, that projects sound. The form was developed as part of a torus, as the repetition of its geometry is cost effective and simple to fabricate. A portion of torus then formed the outer enclosure, with the hard surfaced interior fitting neatly within it. The extended portion of the torus shell formed a peak that was later to form a key acoustic driver of the project. As with all free standing / stand alone projects, the difficulty of the design is how the over all form hits the ground in an elegant and considered manner. This was resolved in the case of Soundforms by creating an inward undercut to the torus, much like a pebble on a flat surface. The designed form was developed via 3d printing technology and prototyped with each iteration. The resultant model could be viewed in 360 degrees, and viewed in the round, allowing a greater understanding of its possible deployment. Interestingly enough, as the models produced were a clearly independent form with a beauty of their own they were also used for marketing, and many were retained by interested parties due to their desirability as objects in their own right.

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Fig 5.4.3 Example of an early 3d model developed by BFLS

Acoustic elements

For large orchestras playing in internal venues, the ability of the musicians to hear each other, in particular for the sections far apart on the platform, relies on the relationships of the enclosing walls and ceiling. Part of the sound reflection between platform walls and ceiling help the communication (ensemble) between the musicians and part of this sound is reflected to the audience. For a smaller orchestra the proximity of the musicians helps the ensemble and the shape and angle of the walls and ceiling will have been considered to project more sound towards the audience. Comparing an orchestra shell used for internal spaces, as in theatres or churches, and an orchestra shell that is used outdoors, the main difference is that the orchestra shell used indoor can rely on the sound reflection caused by the internal surfaces of the building in which it is placed. This assists the sound level on the audience plane. In the outdoor case there is generally a lack of reflection from the environment. To increase the sound level to the audience a ‘Peak’ was developed to project beyond the conductor to reflect as much sound as possible down to the audience. The peak then performs in a similar manner to the ceiling of a concert hall or a flown array in larger halls. As mentioned earlier, this key inventive step came from the development of the geometry of the torus, and the over hanging peak that was developed at the cut line.

The images below show the sound reflections (in red) from two sound sources on the platform with and without the orchestra shell Peak. The “Peak effect”, shows the additional benefit of sound reflections that the Peak is able to provide towards the audience.

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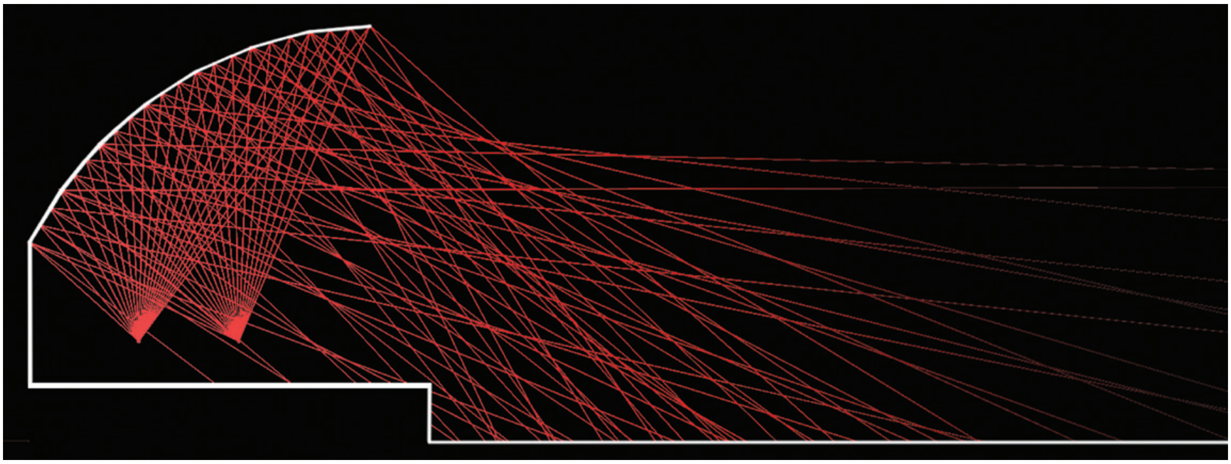

Fig 5.4.4 Acoustic modeling of the shell without peak

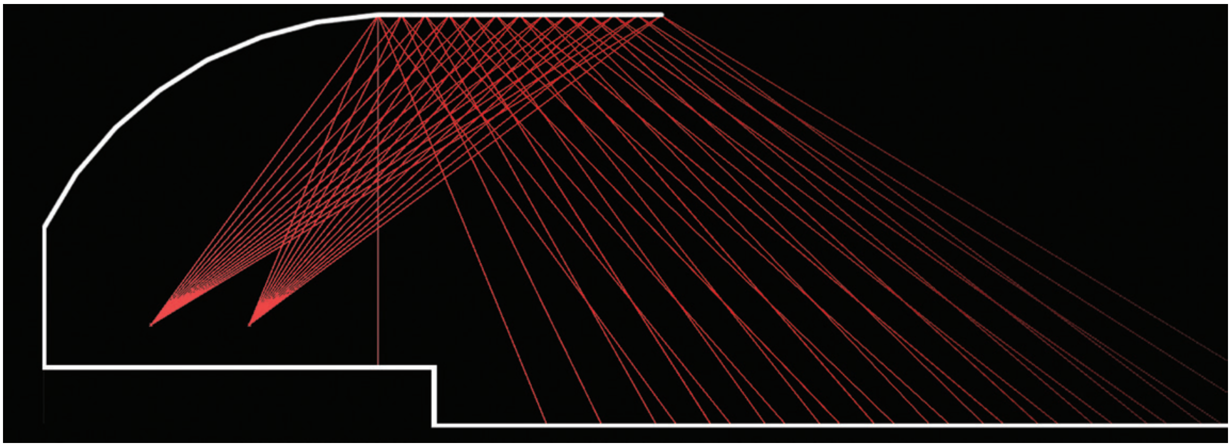

Fig 5.4.5 Acoustic modeling of the shell with peak

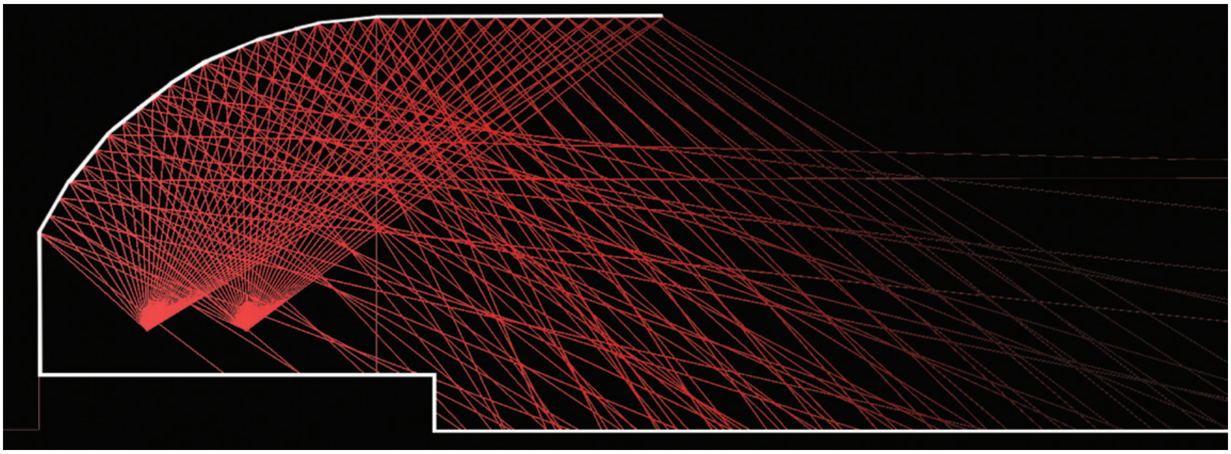

Fig 5.4.6 Acoustic modeling of the shell and peak, showing a greater distribution of sound toward to the audience

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As shown in the images below the use of the orchestra shell improves the acoustic condition for the audience increasing the level of sound naturally transmitted. However, despite this increase, the use of a sound amplification system might be still required depending on the location, existing background noise and audience size.

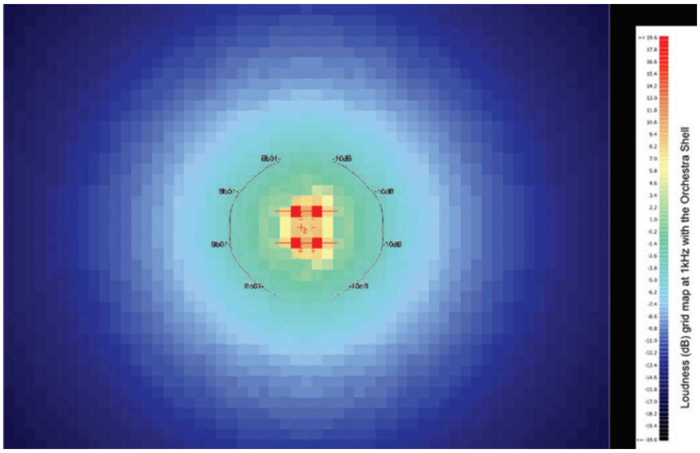

Fig 5.4.7 Sound propagation on the platform: with traditional fabric enclosures sound is free to spread evenly with no control.

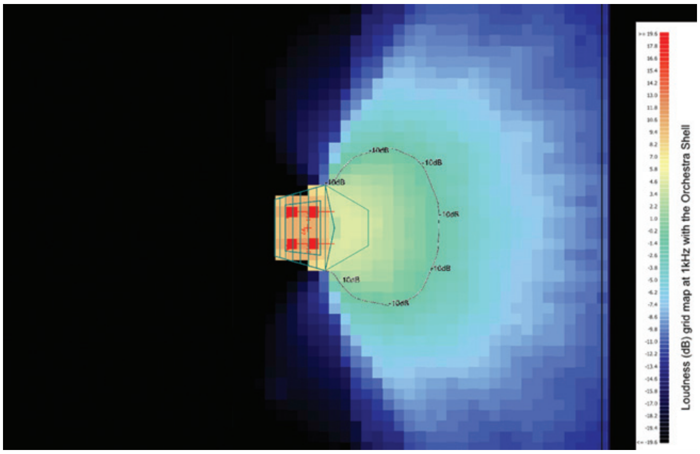

Fig 5.4.8 Sound propagation on the platform: with a shell in place, the sound is controlled and directed toward the audience.

The listening conditions will be affected negatively by a high background noise resulting in a reduction of the signal to noise ratio particular affecting the audience far from the stage. This situation may require a sound system to guarantee acceptable acoustic condition to everybody in the audience. The existence of a built environment around the orchestra shell will affect the sound propagation and could cause negative sound effects such as an echo, so the shell location and orientation on a given site needs to be chosen carefully, of course, orchestral music is usually listened to in a space with reverberation. This provides added warmth and musicality to the performance. In an outdoor event, there is no reverberance for the audience, and so a PA system is likely to be needed for some events where an electronically enhanced sound could provide this effect if the performance requires it.

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Structure

The development of the structure had to address the need to support the outer skin, hold up the acoustic panels, address the concerns of the required form, be easy to assemble, and be easy to demount. The individual elements had to be large enough to work efficiently, yet be small enough to fit onto a typical shipping container. This size constraint was a fairy powerful driver in the development of the structural brief developed by the engineer.

In order to protect against uplift, the structure is mounted on a steel base, holding 40 tonnes of ballast. This ballast can be concrete or tanks containing water or sand, or any material that is easy to transport to and from the proposed site of erection. The shell is supported by an aluminium-trussed structure. For the size of the shell, it was decided that steel would have been prohibitively expensive for the majority of the structural elements. The structure is formed of a series of arches made of interconnected 3 chord truss elements. These were developed digitally with the fabricator; so all elements of the structure could be modelled and coordinated with other elements of the build. The arches were then stiffened by a series of lateral ladder trusses that ran at right angles to the primary arches, holding them in place.

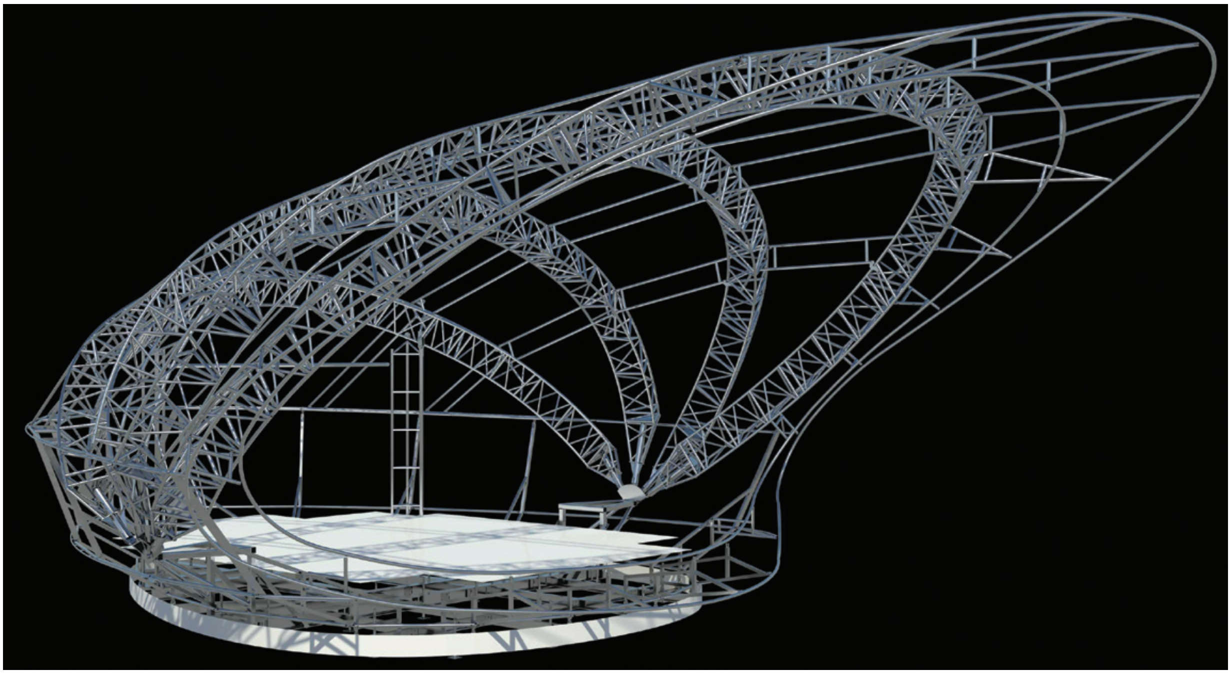

Fig 5.4.9 Working digitally and in three dimensions the team was able to coordinate efficiently, and quickly.

The assembly methodology is based on a pram lid type design, with all of the primary arches being fixed to one rotating pivot point, allowing simple erection by a small team of operators. The first element erected being a simple goal post truss, allowing all subsequent trusses to be braced off this established element. This can be done with a simple forklift truck, or small site oriented vehicle. Cranes are not necessarily required.

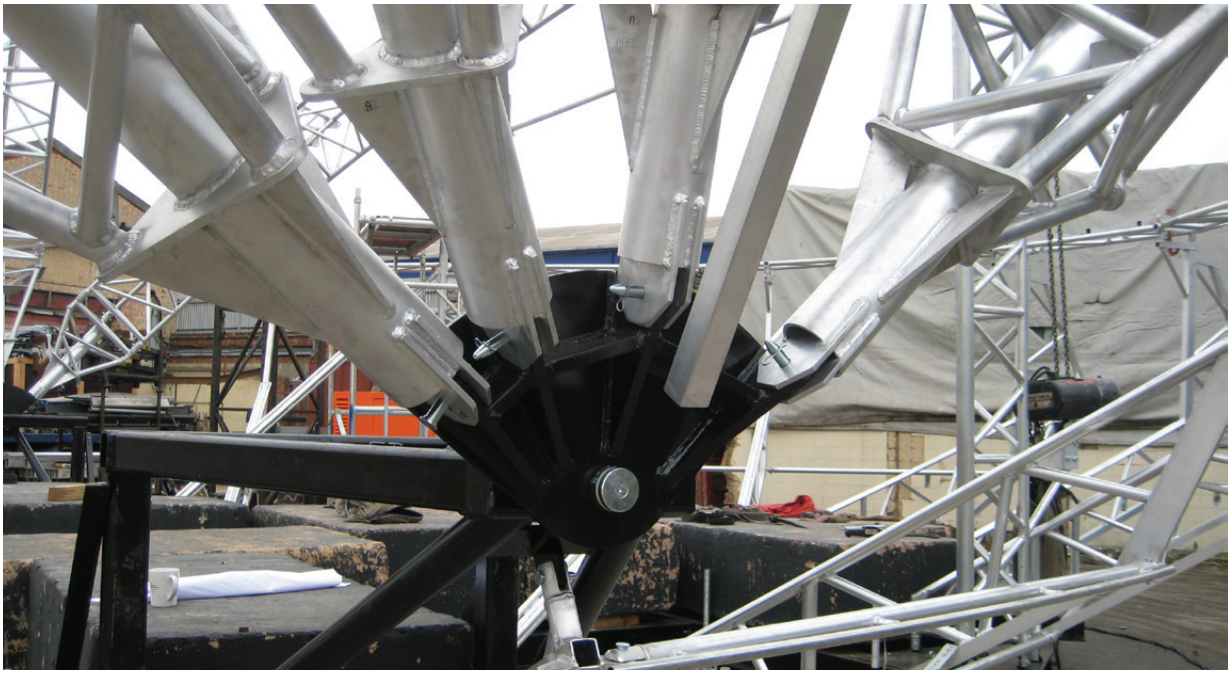

Fig 5.4.10 Photograph of the pram lid joint during the test assembly.

The outer front lip of the shell was of special concern, as it was a defining feature of the form, yet was double curved, and because of cost limitations had to be formed from single curved 40mm CHS. The double curvature was modelled in Rhino, and then optimised into single curved elements; this formed a template for the cutting of the CHS into a single complex curve. The pressures that acted on the curve had to be carefully considered, as the point where the fabric touched the steel varied, and was not ever in the same place twice along the line of the steel.

Fixed acoustic elements

In order to meet the acoustic brief established by the acousticians, a rigid inner skin had to be designed. The skin had to be robust enough to meet the densities required to bounce the sound back to the musicians, and meet the rigors of a touring demountable structure that would take a lot of knocks on the road. The elements that made up the also had to be light enough to be lifted and mounted easily by the shells operators. These conflicting requirements were resolved by way of a series of demountable panels that could be hooked on to a flying truss above the stage. They were easily lifted by a single operator, and were able to be stacked neatly in a manageable collective for easy of transportation. Ultimately the orchestra shell's acoustic skin had to comprise of a series of profiled reflectors constructed from a rigid material with a minimum surface weight of 10kg/m2. This was achieved by fabricating the panels out of 18mm ply, and suspended from the underside of the primary structure by way of simple clips for ease of application / removal. The profile of the reflectors was performance determined, and had to be coordinated within the overall aesthetic of the shell. Concave reflectors were not considered due to the focusing that would occur on the stage, and would confuse the musicians, rather than support them. Flat panels were also not considered due to specular reflections that can lead to a harsh sounding acoustic, a bit like a tiled bathroom. A convex profile was chosen, as this had the effect of distributing the sound around in an even and balanced manner. Their deployment was defined by the acoustic performance within the shell. They had to balance amplitude

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and proximity, if they were too close, there would be too much acoustic feed back to the musician, and deemed too loud, if the panels were too far away, they would be ineffective.

The final layout of the panels was optimized for a small chamber orchestra in the case of the Soundforms that was actually developed to completion. The panels as designed, have a convex plane with, in some cases a plane flat surface running along the rear. This rear surface gives the panels a saw tooth profile along the longitudinal line of the shell. The aim of this profile is to balance the amount of sound that was aimed at the orchestra, and the sound that was directed towards the audience. The size and number of these planes in relation to the convex surfaces had to be sensitively balanced and considered in terms of both acoustic performance and aesthetics. The optimization process was digitally undertaken in Rhino and the genetic algorithm plug in Galapagos. The output of this process was then tested in Odeon acoustic simulation software. When a shell layout was accomplished, it was sent to the architects digitally for integration into the main model. It was then adapted to fit. Obviously this compromised the acoustic in some way, and the model then had to be returned to the acousticians for further modelling. This iterative process continued until there were no longer any compromises, and the aesthetic of the inner shell could be considered as being a visual model of the working acoustics.

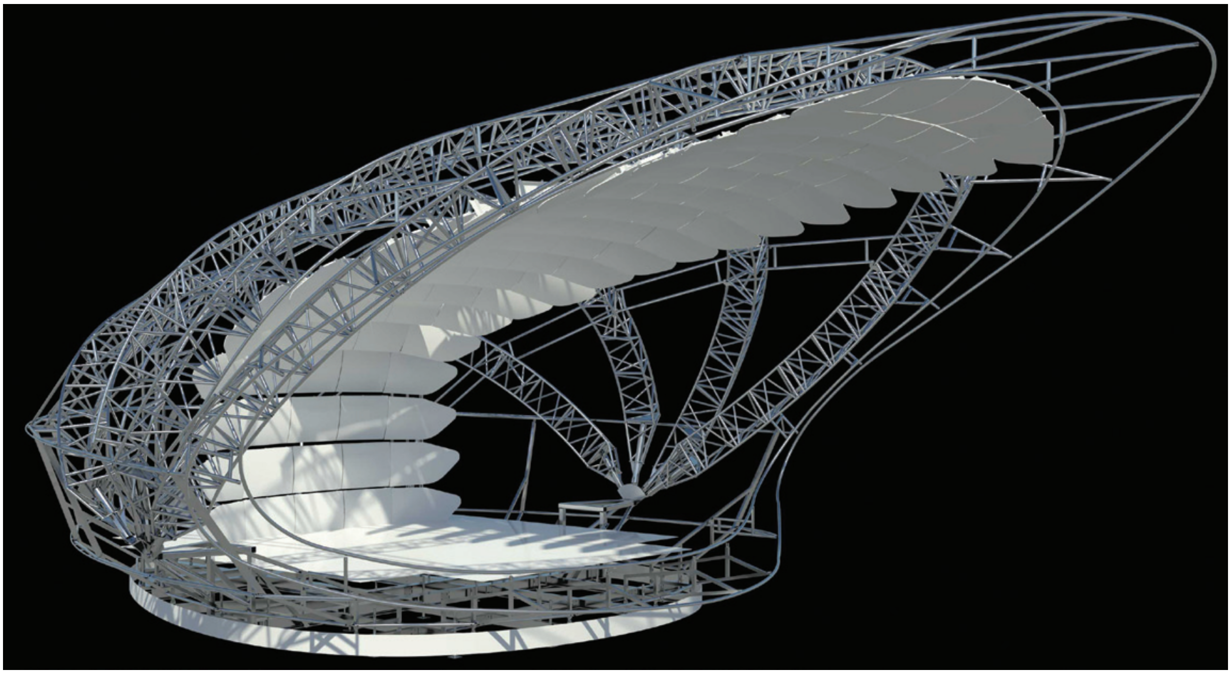

Fig 5.4.11 Computer model showing the acoustic panels in place with the structure

The digital models of the approved panels were then sent to the fabricators, Fineline of Bristol, to be CNC out of large sheets of ply. Originally the diffuse surface required by the acousticians was to be fabricated out of timber battens on a flat surface. This was not in tune with the organic nature of the form, and a curved surface was developed. The curved surface was formed by a series of small channels routed into the rear of the panel, allowing the material to curve, this was held by a simple ply former that was cut to the appropriate radius as defined by the acoustic testing, and then fixed in place. This had to be mocked up as a series of prototypes, and approved prior to fabrication.

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A few differing methodologies were considered, not to create a series of different shapes, but to develop a fabrication technique that would speed up the manufacturing process and use less material. The side cheeks of a typical chamber hall perform in a similar way to the other surfaces and are critical in the acoustic performance of the shell. As the shell that was to be constructed was to suit a small chamber orchestra, these would have to be fairly close to the musicians to be effective. This was in conflict with access issues to the stage, it was decided that the acoustic side walls of the shell could be mounted directly to the inner structure of the shell, with the side cheeks of the stage being created out of a fabric material that would allow the transfer of sound without absorption or colouring it in any way that was detrimental to the core acoustic required. This enabled the core acoustics to work as intended, with the visual aspect of the shell being maintained by a fabric liner. This inner lining is made from Joel elastic, an acoustically transparent material, and totally flexible, performing a little like Lycra.

Fig 5.4.12 Photograph showing the interior during a performance at the Olympic Park, London

The development of the acoustic panels on the interior of the shell utilised no two dimensional drawings in any way, and was developed exclusively through the exchange of computer models and three-dimensional files. Another innovation used was the use of an architecturally trained acoustician from Arup Acoustics based in BFLS office, dealing with acoustically aware architects. The roles of the team were not constrained by traditional office based constraints, and an atmosphere of true collaboration pervaded.

Fig 5.4.13 The acoustic panels being lifted into place during the test in London's docklands.

Skin

As with any mobile structure, the main defence against the weather is key to the success of the structure. This must be light, and easily deployable. Whilst a fabric in some form was a natural starting point for the scheme, there were a few design iterations to be explored prior to deciding on the final version. Tensile fabrics were considered, as were fully inflatable versions, with no reliance on an internal structure. These were looked at, and discarded when issues arose that didn't fully conform to the working design brief. As the process developed, hybrid solutions were considered and modelled. The innovations learned from discussions with fabricators were fed back into the design process, leading to a surface that was seemingly independent of the structure, and was able to curve to the now developing design principles. Ultimately, the design brief was resolved by inflating the outer skin of fabric, rather than a typical tensioned solution.

The weather protection material is a low-pressure inflatable surface that supported the external surface of the shell forming the iconic shape. This was developed by Bath based Tensys, engineering consultants providing specialist services for the design and construction of lightweight stressed membrane structures. The skin had to be analysed in terms of efficient form finding, load analysis and patterning. The original form of the shell was developed by BFLS, and sent to Tensys as a surface model. The core drivers that defined the development of the skin were the performance of the material used to fabricate the skin and the patterning required to form the shape required with an even air pressure applied. The patterning was crucial in the operation of the shell, and the aesthetics, as every panel of the shell was clearly readable on the surface via connecting seams. BFLS worked closely with Architen Landrell the fabricators, and Tensys to establish the rules that governed the application of seams, and their visual impact on the final product.

Tensys used their own software called ‘inTENS’ to develop the shell. The output of the computer modelling was sent to BFLS digitally for evaluation. Following a series of iterative transfers, a final approved shell was developed. This met the requirements in terms of effective patterning that held the shape, matched the logistical demands of the manufacturing process being cut within the size of the source material and had seams that were complimentary to the shape, and not detrimental. Key to the success of the patterning is the depth of the membrane that varies to equalize the air pressure, and keep the external element smooth. The skin was developed as a series of 8 removable waterproof PVC coated polyester cushions. A single skin being too unwieldy to install in one attempt as would be required, the panels were fixed to the structure via industry standard ratchet straps. This is a common fixing methodology in the rigging industry, and would be easily understood by operatives unfamiliar with the shell. The outer skin was fixed via a series of coordinated airtight zips. These were developed by NASA in space suit design, and now commonly used in dry suit manufacture for the diving industry. The inflatable panels were put in place as the structure was assembled, so both elements could be fitted simultaneously, allowing a shorter rigging time. The skin was inflated via a small pump located in the back of the shell. It is housed in an acoustically attenuated box, so as not to disturb the performance. It is a speed controlled centrifugal blower operating at 0-10 volts. The internal pressure of the skin is constantly monitored by sensors that modulate the airflow from the pump, keeping the form in place. The skin is inflated to 50psi, which was found to be sufficient to provide a stable form even in high winds.

Fabrication & Assembly

Architen Landrell based in Chepstow made the skin, the Total Solutions group in Birmingham made the structure, and the acoustic panels were made by Fineline fabrications in Bristol. The structure was assembled in by ES Group in the Docklands. March 2012. The test build took a week to complete, and did not represent the speed of a proper deployment of the shell if commercially deployed, which currently takes three days to erect, and takes two days to demount.

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Testing

In March 2012, the prototype was tested in London's Docklands with players from the London Philharmonic, Nicola Benedetti, and Charlie Siem. The weather was bitter, and the space used to assemble the shell was directly under the flight path of City airport, creating challenging conditions for the performers. Whilst a PA system was present at the test, the shell was tested without amplification, to establish that it worked. The team was looking for two main outcomes in the testing, that the musicians felt the reinforcement that the shell was intended to provide, and that the audience could appreciate a clearer acoustic than previously experienced at external concerts.

Fig 5.4.15 Testing the shell in London's Docklands

The varied nature of the potential sites for the product made acoustic testing fraught with inconsistency. It is impossible to determine where the form will ultimately be deployed, so any test results gleaned from the test site would be meaningless in the context of future deployment. It was simply decided that a series of test performances would be conducted within the shell that represented typical intended uses of the product. These were performances for a solo piano, a solo saxophone, and string ensembles of varying sizes. Each of the performers and selected audience members were interviewed afterwards for comments on the performance of the shell.

The performers commented extremely favourably on the shell, and all felt that the experience was beneficial to their playing. They felt that despite there being no full enclosure, there was enough feedback from the acoustic panels to support their performance. The main points made by the musicians were focused on the 'clarity' of sound in tandem with warmth to the reverberation in the shell.

Charlie Siem, International solo violinist observed: 'I think there is no standard for performing outside, it (has been) just a tent. The difference with Soundforms is enormous.

There is a real sense of the sounds being lifted; its like a concert hall stage, you can hear everyone very clearly, but it feel a lot more intimate. Usually you can't hear anything when playing out doors; this allows for real music making.'

The London Philharmonic noted: 'Very enthusiastic about the whole thing … really enjoyed the experience of playing in it … the sound was great and it is a very exciting idea. It looks fantastic. Everything inside the structure was good, lighting, space to move, acoustics etc.'
Iain Bellamy, Saxophonist ECM Label concerned: 'The Soundforms acoustic performance shell took me quite by surprise! From an audience perspective I beheld a futuristic and magically illuminated stage … that projected the music with perfect clarity. From a players perspective I enjoyed its acoustically comfortable performing environment and clear sonic focus from which I could sense the quality of sound emanating from the stage as I played. I expect to see the shell become a regular sound and sight at music events in the near future.'

The audience comments were equally favourable, with many members who were asked commenting that they had tested the scope of the shell by walking in, and out of the zone of support given by the shell. By way of analogue testing in this manner, it was confirmed that the shell did indeed project acoustically towards the audience, improving the natural acoustic for the audience members.

Lessons learned

Whilst the acoustic of Soundforms was an unqualified success, the team learned a great deal from the prototyping experience, and have agreed a few design changes that have come about from the experience. The aluminium structure will now be constructed of steel, to last longer, and be more robust. The three-cord truss system was deemed to take up too much space, and has now been developed into a series of ladder trusses that are flatter, and can be easily stored. Finally, the ratchet system that holds the skin in place on the structure, was developed as it allowed an operative to individually tailor the tensioning of the outer skin on the structure proved too flexible, and created irregularities along the key system lines of the fabric. It has now been decided to use a less variable shotgun profiled extrusion to key in the raised rubber edge sewn into the edge of a fabric panel, the cada, this keeps the skin in constant tension, and smooths out the final form.

Deployment

The testing process was successful enough that it was then selected by LOGOG for deployment in the Olympic Park for the 2012 London Olympic Games, where it hosted almost continuous performances for the duration of both Olympic and Para-Olympic games. Despite being used by mostly amplified ensembles, the feedback from the performers was wholly positive.

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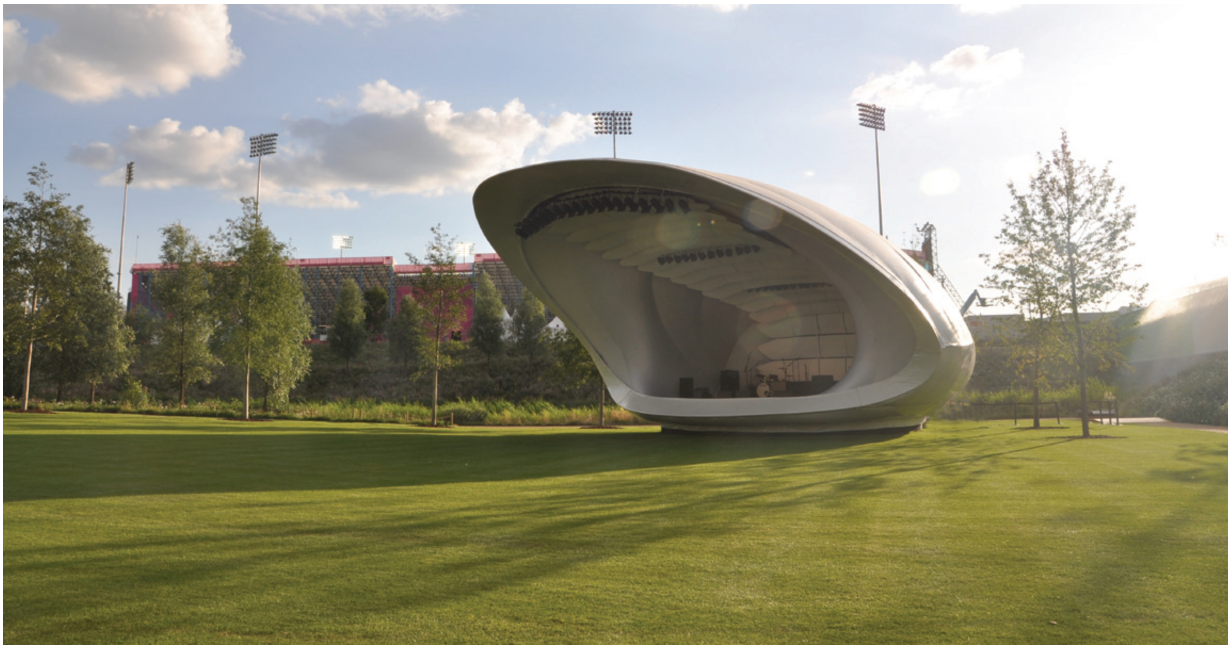

Fig 5.4.16 The shell in the Olympic park.

Fig 5.4.17 The shell in use in the Olympic park.[ii]

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Credits

Design Team:
Mark Stephenson, Conductor
Jason Flanagan, BFLS
Paul Bavister, BFLS
Ian Knowles, Arup Acoustics
Olly Watts, ESG
Engineering:
Malcolm Richards:
Andy Prescott
Skin development:
Tensys
Fabrication:
Total Solutions Group
Fineline
Architen Landrell
Acoustic Modelling:
Luca Delatore
3d Modelling:
Armando Elias
Matthew Donkersley
Andrea Vannini

References

i Paul Bavister graduated from the Bartlett School of Architecture in 1999, and is an Associate Director at BFLS, and a Director of Soundforms.

ii Image Credits: Fig.1,11-12, 15 and 17 © N Guttridge, Fig. 2 © Hekman Digital Archive, Fig. 3, 9-11,14 and 16 © BFLS. Fig. 4-8 © Arup Acoustics.

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