Design, construction and analysis of a concrete shell using clay formwork, augmented reality and sprayed concrete

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Abstract

Concrete shells offer high levels of structural efficiency and durability, particularly where large spans are required, and dead loads dominate. This project responds to a unique brief for large, enclosed spaces beneath soil and grazing livestock. This made a concrete shell a strong option. Before embarking on that, a smaller prototype was designed, built and assessed. Innovations included the exploration of hybrid textile and steel reinforcement, sprayed concrete, and a shaped clay mound as formwork. Augmented reality was used throughout construction to guide the placing of the clay, formwork and the reinforcement. The success of these was evaluated through lab tests on sprayed concrete samples and a digital point cloud geometry scan, which was analysed to assess the structural impacts of geometric imperfections. This combination of extensive design exploration, construction innovation and abundant data collection revealed many lessons learnt.

Keywords: Concrete; shell; augmented reality; textile reinforcement; sprayed concrete; formwork

1 Introduction

As part of the redevelopment plan of their landfill site near Royal Wootton Bassett, in South West England, Crapper and Sons Landfill (CSL) commissioned Format Engineers, in collaboration with Architects Designscape Ltd, to design a number of long span (40m x 40m) thin concrete shell structures which are intended to be part buried under pasture fields and which will house laboratories, food production and storage, **Error! Reference source not found.**. The University of Bath were engaged by CSL to work alongside Format Engineers, providing expert guidance on textile reinforcement and shell design.

Figure 1. Render of the proposed full-scale shell

Before embarking on the final design and construction of the full 40m version the client wished to investigate novel structural analysis, design, material and construction methods on a smaller scale prototype, which if proven to be successful, would be applied to the full-scale shell. Format Engineers were responsible for developing that test structure into a form which encapsulated all the potential technical and practical challenges of the large shell in a small 7.3m x 7.3m x 3.4m high variant. Format Engineers were also responsible for the digital modelling of the data for fabrication, Figure 2.

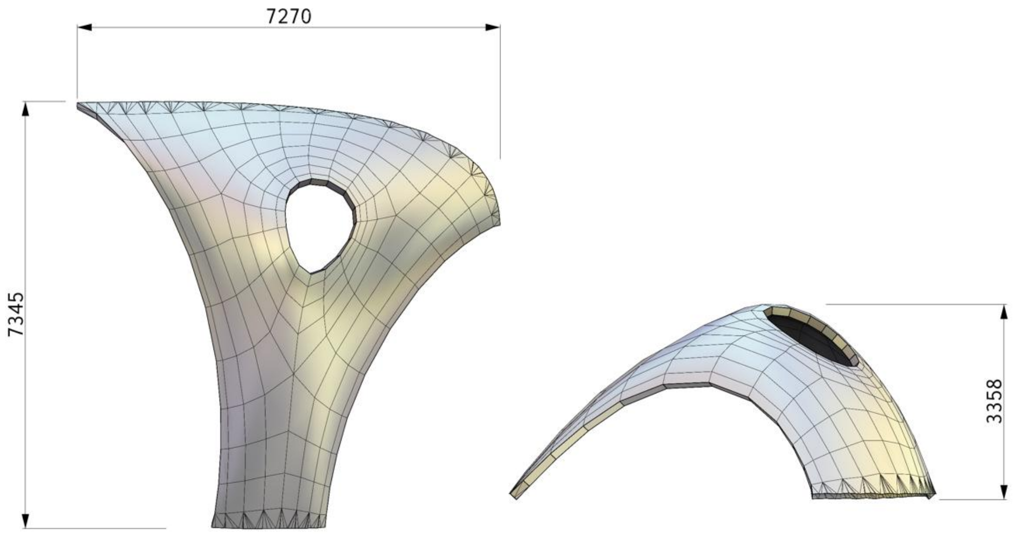

Figure 2. Dimensions of the mini shell

2 Elements of the construction

The small-scale shell prototype shares several details with the large shell. The hope was that if these ideas were proven to be useful on the small prototype they would be adopted in the construction of the main shell.

2.1 Geometry

There are a number of well-established form finding techniques for shell structures. This project used a dynamic relaxation script within the Grasshopper plug-in to Rhino to generate a double curved shape with a single 'leg' and a longer linear rear support. It is anticipated that the final 40m variant shell will curve into several discrete 'legs' together with a long linear support hence the need to test these features within a smaller prototype. The shape was also chosen because the linear support produced a surface of relatively flat curvature over a plan length of the shell (another prominent feature of the larger project) and because it mimicked one of the several radial window openings in the roof of the large shell.

2.2 Reinforcement

The client wished to investigate glass textile reinforcement in lieu of traditional loosely laid reinforcement bars whenever possible. The primary motivation for the use of glass textile reinforcement was speed and ease of construction, and its corrosion-resistance also brings durability and reduces cover requirements, which is effective in minimising overall thickness for concrete shells. As part of the development work on the large scale project Format Engineers had developed a parametric script based on a research paper published by the Block Research Group (BRG) at the Institute of Technology in Architecture at ETH Zürich [i] which can discretise principle stresses in a shell into a simpler, more practical pattern and hence more efficiently orientate reinforcement bars or textile weave on a double curved surface. The prototype was a chance to test that research. In tandem with this, we aimed to develop textile reinforcement cutting patterns which were aligned to the efficient principal stress orientation, and which also respected the double curved geometry of the shell. The maximum width of the flat sheets of glass textile was a limiting factor in the patterning, Figure 3.

A model of strength utilisation for glass textile reinforcement was implemented based on research at the University of Bath[ii]. From initial investigations, it was found that some conventional steel reinforcement will be needed in the large-scale shell, in particular where it meets the ground floor slabs and foundations, so the analysis was modified to include a hybrid reinforcement with both a textile mesh and conventional steel bars. However, the strength contribution of a practically sized textile mesh was found to be small compared to steel bars, necessitating its use in multiple layers, each of which would require an additional concrete layer to be applied. As such, it was decided to use steel bars only in the constructed design.

Figure 3. Textile reinforcement patternation

To relieve stress in the interface the joint between foundations and shell is idealised as a pure pin which requires the adoption of a specific reinforcement detail where the only bar through the joint is a single element in the middle rather than at the extremes where it would transfer tension or some compression force. This concept was tested in the small-scale prototype.

2.3 Sprayed concrete

A further ambition of the test project was to invest in a sprayed concrete technique more commonly used in below ground tunnel lining construction rather than hand pouring, compacting and shaping.

The concrete mix was a 10mm aggregate CEM1/GGBS cement based mix with Sika additives.

2.4 Formwork

Rather than conventional timber or steel formwork, Crapper and Sons used a shaped clay mound as that material was freely available on site. To shape the clay form, to place the formwork and accurately place the reinforcement an augmented reality (AR) Microsoft Hololens was used rather than traditional line and level surveying techniques, Figure 5 and Figure 4

Figure 4. Site operatives using the AR platform

Figure 5. Hololens representation of the clay mould

3 Construction

The erection of the shell started in November 2021 with the construction of the foundations. The AR based platform was used to place the reinforcement. The shaping of the clay bound mould was completed in mid-December 2021, **Error! Reference source not found.**. Spraying of the concrete took place early April 2022, and the clay formwork excavated later that month, **Error! Reference source not found.**.

Figure 6. Completed clay mould

Figure 7. Completed prototype she Construction survey

4 Post Construction surveys

4.1 Point cloud survey

In summer 2022 the client commissioned a laser point cloud survey, Figure 8, to compare the dimensional intent as modelled in the Rhino 3D software (which was used as the basis for the Fologram/Microsoft Hololens augmented reality workflow) with the reality. The results were made available in a proprietary point cloud format which was then imported into Rhino 3d, a nurbs based commercially available 3d modelling software.

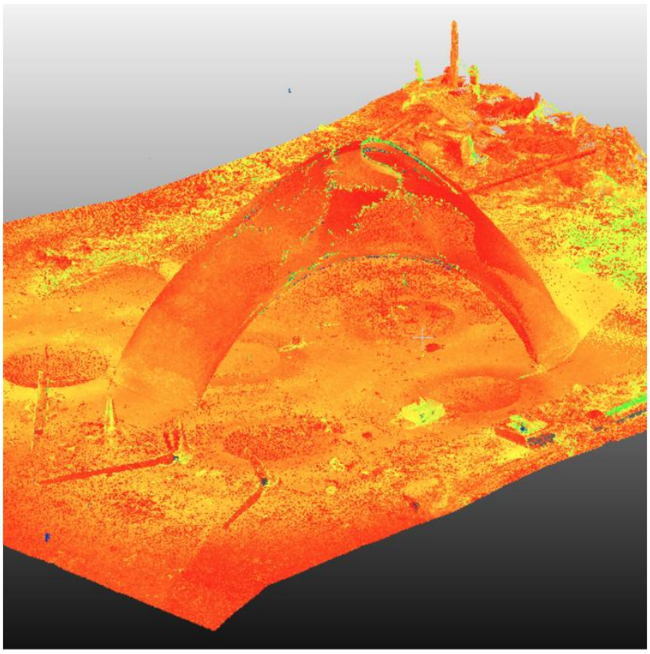

Figure 8. Point cloud survey

Using the parametric modelling environment Grasshopper within Rhino 3d the point cloud data was aligned with the original model. Several techniques were used, including at first a manual rotation, then bounding box alignment and finally an 'iterative closest point' algorithm, Figure 9.

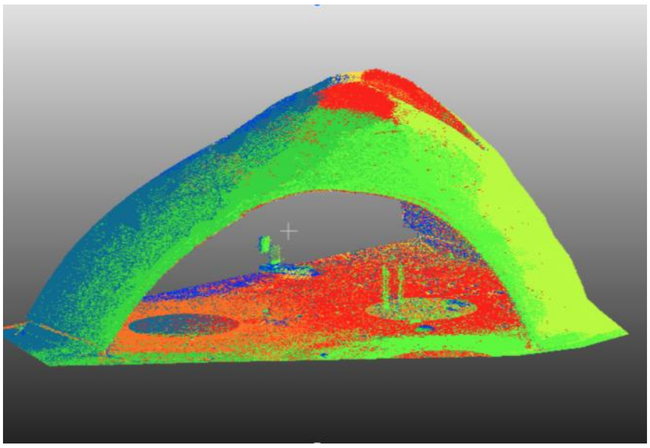

Figure 9. Point cloud survey after editing

The results of the as-built shell where then compared to the intent, Figure 10 and Figure 11. The deviation in millimetres as a colour contour has been employed to highlight the magnitude of the imperfections.

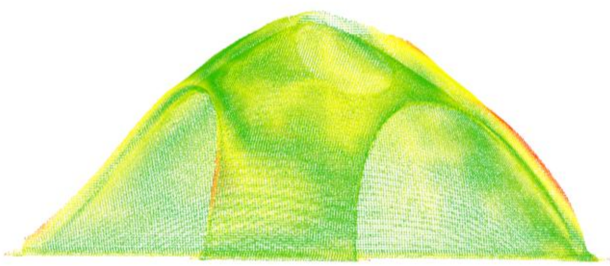

Figure 10. Deviation of shell as built from theoretical model - elevation

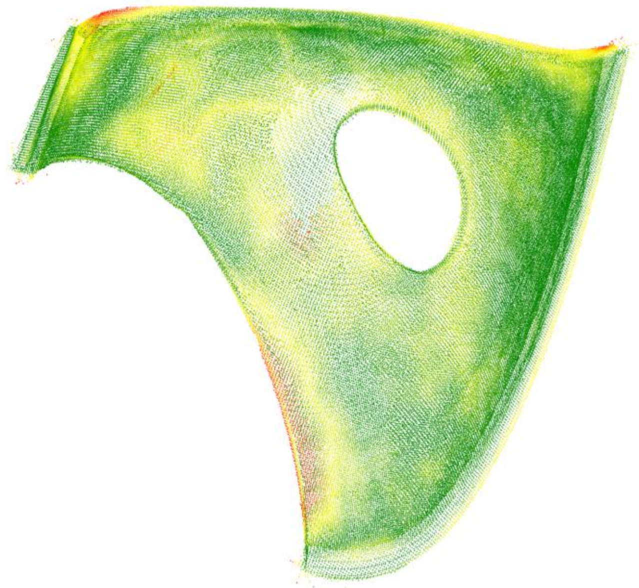

Figure 11. Deviation of shell as built from theoretical model - 3d view

The fit of point cloud survey over the theoretical model is not completely accurate due to tolerances of fit but a general picture is clear, and valuable conclusions can be drawn. The shell is at worst 200mm out of alignment with theory at the free edge. This is shown in red. It is 200mm away in a positive direction based on the normal vector of the shell at that point. There are other areas of 200mm variation near the footing of the shell and a very local deviation almost at the apex of the shell. Elsewhere the correlation is in the main between 0 and 70mm.

4.2 Visual inspection

The authors visited the site in May 2022 to carry out a visual survey of the shell. Some large cracks and geometrical inconsistencies were evident. ,Figure 12 The cracks were not measured in length or width, but their location was noted and a view taken as to what they had propagated. The rough texture of the concrete makes measurement of the crack and tracing its full length difficult, but the cracks were felt to be related to flexural cracking of the concrete following global movement of the shell. A view was taken that they would not affect the integrity of the shell. There were several areas where the concrete had poorly been compacted.

These are concluded within the appendix to this paper.

Figure 12. Cracking of the concrete

5 Structural comparison - as built to theoretical form

It is assumed that even after some experience using the augmented reality construction workflow to shape clay moulds and with shorter time periods between completing the mould and spraying the concrete some variation in shell geometry will still occur on future applications.

To test the effect of this a new structural model was created from the point cloud survey and analysed in the same manner using the same loadings as the theoretical shell. The mesh derived from the point cloud survey had significant local discontinuities in geometry. Those due to the construction process were described earlier but at the top of the outermost surface of the shell there is a dip where presumably it was not possible to obtain point cloud data. From comparison with site photographs that dip is not present in reality and hence was part smoothed out in the model Figure 13.

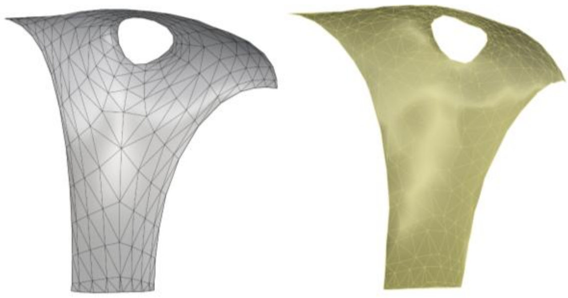

Figure 13. Theoretical and as built analytical mesh models

5.1 Loadings

The mesh models of the pure theoretical geometry and the mesh obtained from the point cloud were generated in the Rhino/Grasshopper environment and then exported to Oasys GSA finite element solver. The shell was specified as 150mm deep. Loads were added to each model which mimic those which will be applied to the main shell, namely; Super dead load - 10.8 kN/m2 representing 600mm of soil and an Imposed load - 5.0 kN/m2. An ultimate limit state (ULS) combination of 1.35 self weight + 1.35 Super dead load + 1.5 Imposed load was calculated. The loads were applied uniformly, Figure 14.

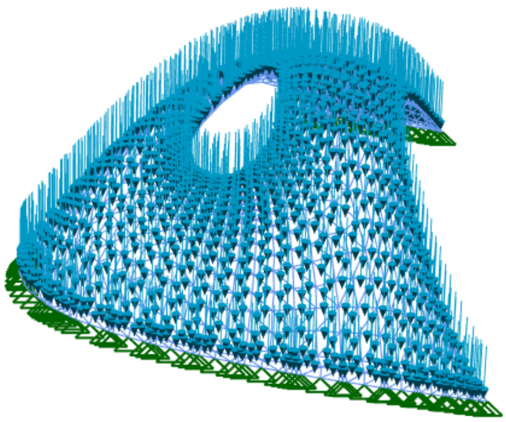

Figure 14. Applied SDL

5.2 Ultimate limit state results

The results from the analysis are set out below. We have included two sets of results, the Von Mises derived stress in the top surface of the shell and in the bottom surface, Figure 15 and Figure 16. These are the critical values for the reinforcement design of the structure. A plot of deflection under full ultimate state combination loads is also included. This is more adverse than the values that would normally be used as a measurement in detailed design but serve to highlight the potential total movement of the shell and act as a valid comparison between before and after structures.

5.2.1 Derived stress

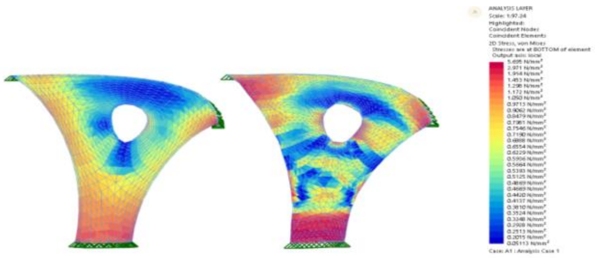

Figure 15. Derived Von Mises stress - shell bottom layer

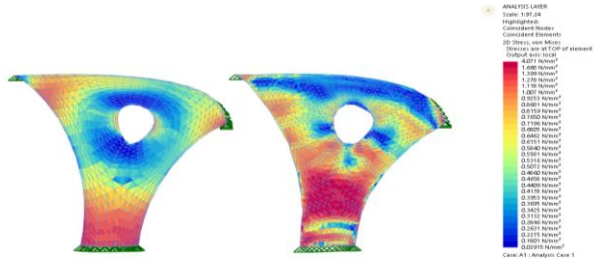

Figure 16. Derived Von Mises stress - shell top layer

The above results show that discontinuities have a significant effect on the performance of the shell. The additional bending moments introduced by the unplanned steps in geometry propagate through the shell. These can be seen in comparison with the 'purer' form found geometry of the theoretical model which is primarily transferring vertical load by in-plane resistance. See later discussion on the implications for the main shell.

5.3 Deflection

A hugely exaggerated scale plot of deflection is shown below, Figure 17. These emphasise that geometrical discontinuities introduce out of plane bending moments which propagate through the structure.

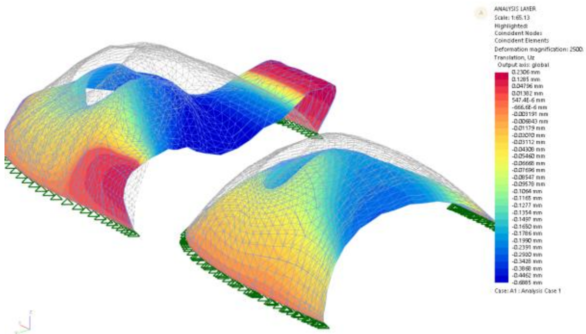

Figure 17. Deflection 3d view

5.4 Commentary on structural findings

The above findings show that deviations in geometry due to the construction process have a demonstrable effect upon the performance of the shell. In our view the values of stress increase cannot be directly scaled up as the shell form is slightly different, the point cloud survey was not entirely complete and the influence of span on axial load in the shell and hence the degree of out of plane bending cannot be easily scaled up.

Our suggestion for the analysis of the main shell would be to acknowledge the effect of construction errors and to include deliberate geometrical imperfections of the same magnitude as the test shell within the final main shell geometry. The practical implications will be an increase in reinforcement (the amount of extra reinforcement is outside of the scope of this study) and design time but compared to the efficiency savings in using the Microsoft Hololens.

6 Sprayed concrete structural testing

Coinciding with the construction of the mini shell prototype, three flat concrete panels of nominal 200mm thickness were cast; one with steel reinforcement, one with textile reinforcement, and one unreinforced. These were cut into beams approximately 200mm wide and tested in four-point bending to determine the performance and consistency of the sprayed concrete construction process. As for the shell, the full thickness was built up in two layers, creating an internal interface between spraying operations. Three 100mm cube samples were also obtained from the specimens and tested in compression, with an average of 25.7MPa being below that expected, the likely cause of which was poor compaction between spraying layers. The unreinforced beam flexural tests revealed an average tensile strength of 1.59 MPa, lower than that expected from the compression tests, which also indicates an unusually high presence of flaws.

Poor compaction of the concrete did not affect the flexural performance of the steel-reinforced beams, however, which all developed their full expected ductile flexural capacity whilst failing consistently at regions of minimum thickness, Figure 18, In contrast, the beams with textile reinforcement, whilst having some post-cracking strength, failed in a brittle manner. Figure 19 shows the failed section, with the spraying layers and ruptured reinforcement visible.

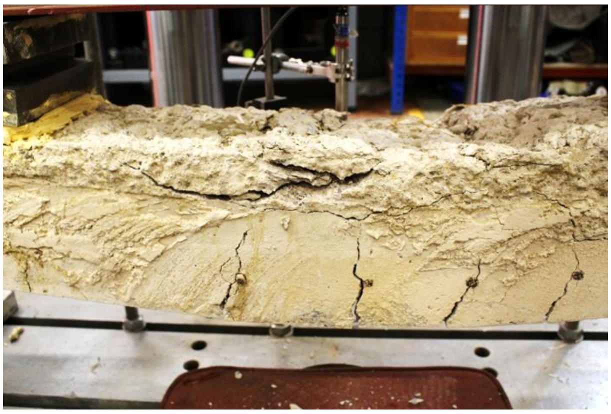

Figure 18. Flexural failure of steel-reinforced beam sample showing distributed cracking and concrete crushing, indicative of safe, ductile failure

Figure 19. Flexural failure section textile-reinforced beam showing ruptured reinforcement and concrete layer inconsistency.

The tests showed that the concrete spraying process can lead to a reduction of concrete strength properties, but also that steel reinforcement can mitigate the effects of this (in flexure) through the ductility it provides.

7 Discussion, Conclusions and Acknowledgements

From observation of the shell during the visual inspection of May 2022 and from later discussion with the client/builder a number of lessons were learnt.

- Textile reinforcement is not practical in a small shell of tightly curved geometry. The narrow standard roll size makes the nesting of cutting patterns very inefficient. The flatter full size shell may still be suitable for the use of textile reinforcement. At the time of writing this has not been tested.
- The clay mould was left far too long between completion and spraying of the concrete. The clay was left four months before the first concrete application. This was long enough for it to dry and shrink as the moisture content lowered. This can be seen in the texture of the inner face of the

shell. The 200mm deviation in the as-built shell is partly attributed to the clay shrinkage.

- The construction used the first generation of Microsoft Hololens. This was not accurate enough in practice. It used a single reference point, and the model moved in relation to that, compounding inaccuracy. The second generation of Hololens which uses multiple reference points may be more accurate. Tests on subsequent projects have confirmed this assumption.
- In practice the Hololens was still useful in several areas; in shaping the clay mould, in setting out reinforcement and in locating and shaping the formwork. The contractor would use the AR platform again for these operations.
- The long free edges of the shell were challenging to set out as they required a flat surface to change in orientation along the length of the edge curve. This was very difficult to construct.
- The concrete spraying was not carried out with the Hololens. The client believes that this was not applied correctly due to poor performance by the sprayed concrete contractor. This may have contributed to the cracking in the concrete, overspray and the variation in concrete depth. The extent of this is difficult to quantify.
- One practical lesson learnt for future shell construction would be the use of 'depth pins' of plastic, stainless steel or similar which are set into the clay mould and which provide a benchmark for concrete thickness. These would be cut off after the clay has been excavated.
- The contractor has also commented that a finer, smaller, aggregate concrete would be considered in the future.
- It was observed that spraying the top of the shell was difficult. Consideration will be given in the future to spraying from a cherry picker or movable platform.

Deviations in as-built geometry because of the construction process should be factored into the final shell design. An allowance would be made for additional reinforcement and design time/resource.

8 Conclusions

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9 References

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