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3D Scanning and structural analysis of Heinz Isler's shell for swimming pools

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Abstract
During his live Heinz Isler built around 1400 shell structures. In July of 2012 Borgart and Eigenraam from Delft University of Technology went to Isler's office during two days to make 3D scans of his scale models. His scale models were being inventoried so they could be taken to the ETH Zurich to be studied and archived. This paper presents the process of structural analysis of Heinz Isler's shell for the Heimberg Swimming pool. For that purpose the geometry of the shell was obtained through an additional 3D scan at location. The resulting point cloud has been processed into the basis for the shells geometry and subsequent structural analysis model. This process will be elaborated in different parts. It will be described how the geometry of this shells was form found by Heinz Isler. Point clouds have been obtained as a results of the 3D scanning, and the require processing to be used as structural FE models. This will be described including the cleaning-up of the point clouds as to come to an sufficiently accurate surface fitting before this geometry can be used as a FE model. Using the FE models an assessment is made on the performance of the shell, this included a study of membrane and buckling behaviour. The models and results will be presented along with the assessment of the shell's performance.

Keywords: Heinz Isler, 3D scanning, point cloud, reverse engineering, surface fitting, shell assessment, buckling, Heimberg Pool.

1. Introduction
In Heinz Isler's momentous conference presentation "New Shapes for Shells" at the First Congress of the International Association for Shell Structures in Madrid in September 1959 Heinz Isler proposed three innovative form-finding methods for thin reinforced concrete shells [1, 2]. Of these, the "hanging cloth reversed" was, in his opinion, the best. However, it was not until nearly 10 years later that he designed and built shells using this form-finding method.

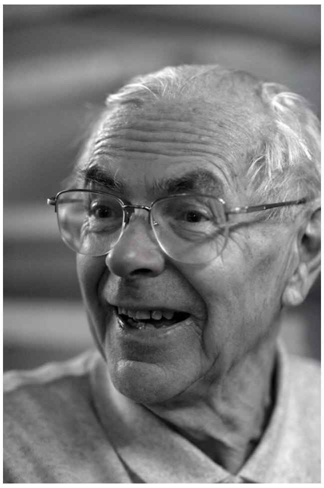


Figure 1 Heinz Isler in 2006 (Photo: ©wilfried-dechau.de)

The first three – a laboratory and research building for Gips Union AG, Bex, an architect's office building, in Sargans and two triangular shells for the Deitingen Süd motorway service area, all in Switzerland, were completed in 1968. These were followed, in 1969, by the completion of the most complex free-form, on seven supports, for Sicli SA, in Geneva; a 16x16m square-plan swimming pool roof at the Hotel Splendide, Lugano (1972); and outdoor theatre shells in Stetten (1977) and Grötzingen (1978) the last two in collaboration with architect Michael Balz [3].

The square-plan Heimberg swimming pool shell roof, near Thun south of Berne, Switzerland (Architect: H. Maier), which was also completed in 1978, spans 32.5 x 32.5 m, and has a minimum thickness of 90 mm. Demonstrating the appeal of this design, almost identical, but slightly larger (35 x 35 m), swimming pool shells were built later in Brugg, Switzerland, in 1981 [4] and Norwich, UK, in 1991 [5, 6]. The shells cover four times the area of the Lugano pool shell and have some resemblance to the main hall of the Sicli shell. Referring to the Heimberg shell in his paper presented at the World Congress on Shell and Spatial Structures: 20th Anniversary of IASS, held in Madrid in 1979, Isler commented that "This double curved shell is rather flat and elegant. I consider it to be the simplest shape on four supports one can imagine." [7].

Figure 2 Heimberg swimming pool (Photo: Archive Isler)

Figure 3 Heimberg sport complex (Photo: Archive Isler)

These simple shapes, as Isler considers them, are subject of study in this paper. Membrane and buckling behaviour are studied by comparing two scale models. These models were present in his former office in 2011. Two of the authors travelled to Lyssachschachen, Switzerland to scan many of the scale models among which the models in this paper. Currently these models are present in the gta Archive, Eidgenössische Technische Hochschule in Zürich, Switzerland. The points clouds resulting from the scans have been processed into finite element models for the studies in this paper.

The plan size of the models suggests that these models are for the Heimberg and Brugg pool roofs. The models have a scale of 1:50. In Figure 4, the left model is slightly smaller. Scaling of the model results in the size for the Heimberg shell. A remarkable difference with the built shell is the shape of the arched edges. In the built shell they curve upward in section while in the scanned model they are relatively flat. This difference and the finishing of the model, see Figure 5, possibly indicates that it was an early presentation model. The right model, also Figure 6, scales to the size of the Brugg shell. Its shape is slightly higher and edges curve upward.

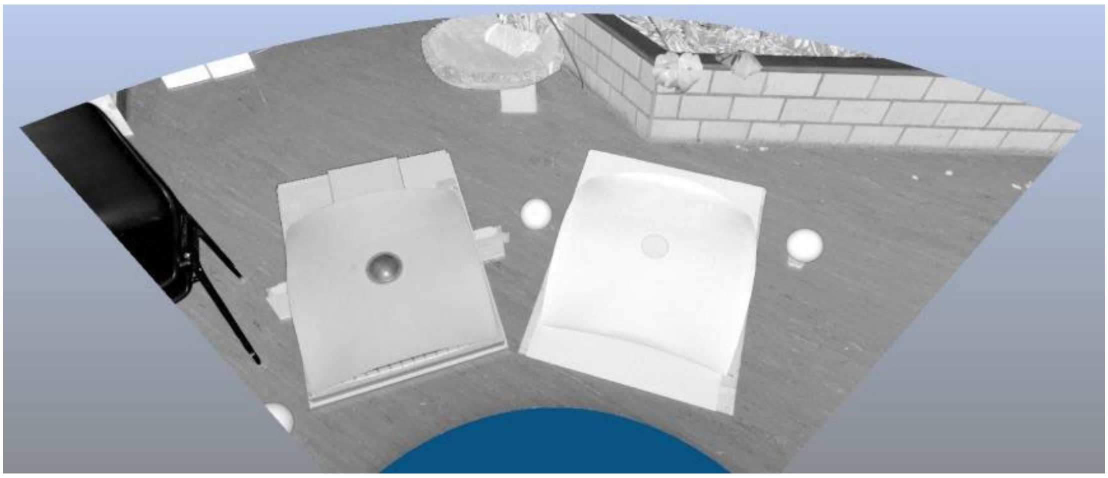


Figure 4 The two models. Left presentation model and right the model with curved edges (Image: Peter Eigenraam)

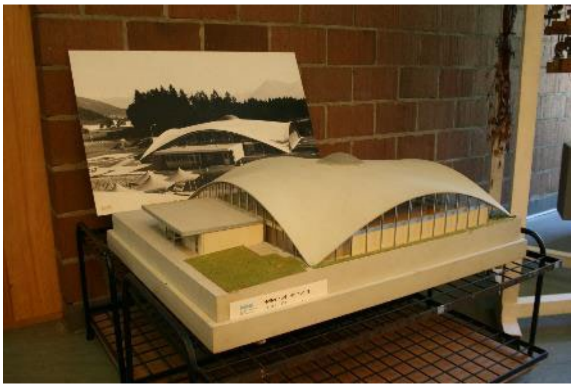


Figure 5 Presentation model (Photo: Peter Eigenraam, 2011)

Figure 6 Scale model (Photo: Peter Eigenraam, 2011)

Isler was always concerned with the potential for instability in thin shells and in a conference paper [8] he listed "snapthrough; local buckling of the surface; buckling of edges; torsion of segments (windwheel effect)". He then described how, with his extensive practical experience, he had developed rules designed to avoid this possibility. In the paper he showed a picture of a physical model used to study potential buckling of his largest (58 x 52 m) bubble shell, constructed in 1960. He commented that this study decided the thickness of the shell and that the rise (1/7 of the diagonal span) was greater than normal for his bubble shells. As revealed recently, by the 1970s, although Isler continued to use physical models for form-finding of the elegant and efficient shell forms, their structural behaviour was being assessed using finite element analysis, performed by external computer bureau [9]. Nevertheless, in his basement he built a uniformly-loaded, thin reinforced polyester physical model of the Heimberg shell, which was still there at the time of his death in 2009. This was designed to explore potential buckling modes of the surface, two of which can be seen in Figure 7 and Figure 8.

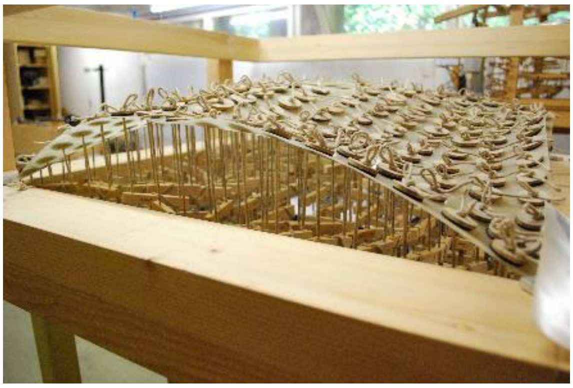


Figure 7 Physical model demonstrating potential edge buckling of the Heimberg shell at midspan (Photo: John Chilton)

Figure 8 The same physical model showing an alternative potential buckling mode of the Heimberg shell (Photo: John Chilton)

Having these insights and data collected, in this paper the authors aim to quantify the membrane, using stress ratios, and buckling behaviour of the two shells. The difference between the “flat” and curved edges provides an opportunity to study its effect in order to gain further insight into the design and knowledge underlying the design of these remarkable structures.

2. Modelling of the shell

The process of reverse engineering the geometry and creation of a finite element model of the two shells was done in a similar way to earlier work by the authors. Detailed steps and underlying explanation are described in [10]. Although the creation of the geometry for every shell has some unique steps it involves generally the same steps and challenges. The process for these two shells is briefly outlined in this section.

2.1. Point cloud and geometric modelling

The scale models have been scanned and the data processed. A 3D scanner has been used which provides point clouds. The point clouds showed slight asymmetry. This has been averaged such that a symmetric model has been obtained. The physical models respectively have a size of 64 x 64 and 70 x 70 cm. The created surfaces are shown in Figure 9 and Figure 10. Non-Uniform Rational B-Spline Surfaces (NURBS) have been fitted to the point clouds accordingly [10]. Therefore, various surfaces were fitted in order to find a best fit. These surfaces had different grid densities of control points and have been compared for accuracy of fit. The degree of the used NURBS surfaces is 5 such that a high level of geometric continuity is secured. Figure 11 and Figure 12 shows the statistical data of accuracy of fit for each surface on the point clouds. Smoothness may decrease with a denser grid. Therefore, based on these figures a grid of respectively 7×7 and 10 x 10 have been chosen. For further reference the name Model 1 will be used for the Heimberg shell and Model 2 for the Brugg shell.

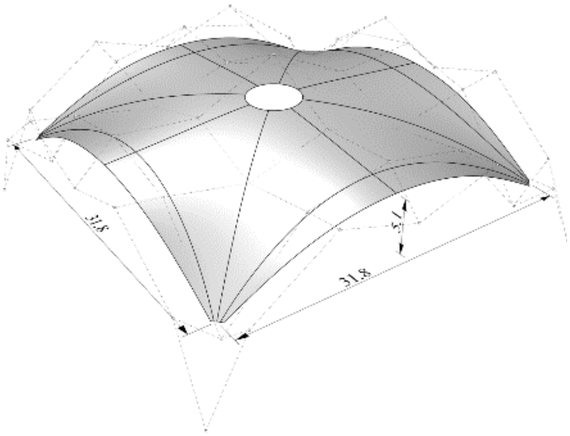


Figure 9 Final surface for the Heimberg shell

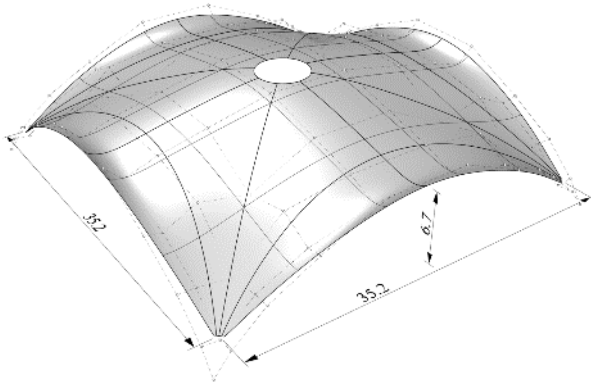


Figure 10 Final surface for the Brugg shell

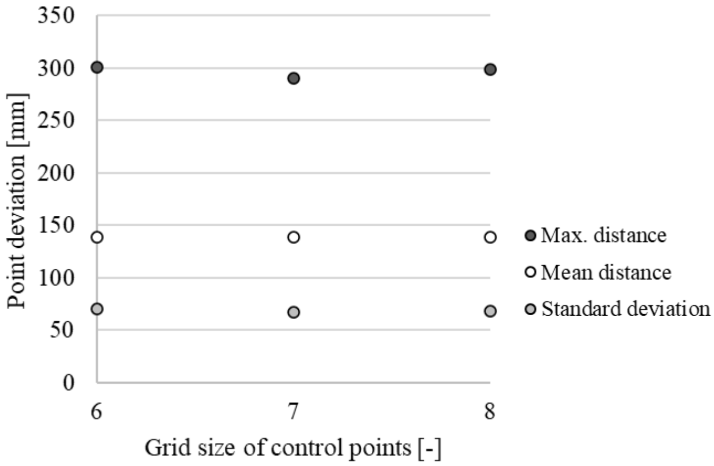


Figure 11 Point deviation for the Heimberg shell (Model 1)

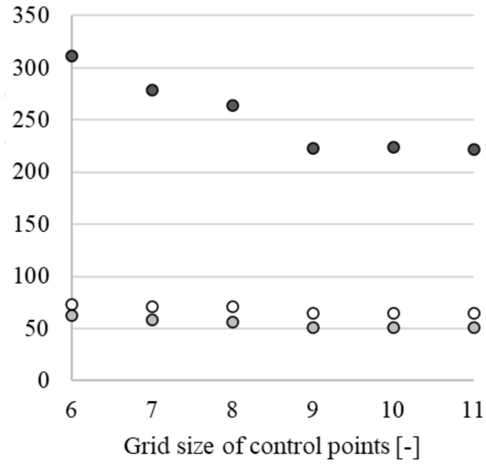


Figure 12 Point deviation for the Brugg shell (Model 2)

2.2. FEA models

The finite element model has been made within the software package Diana FEA. The thickness of the shell varies over the height and has been derived from archive drawings of the Heimberg Swimming pool and applied to both models and implemented as in the models. The value at the base was interpolated linearly from the lowest two positions in Figure 13.

Height [m]	Thickness [mm]
0	424
0.31	350
0.52	300
1.13	200
2.2	90
3.12+	80

Table 1 Thickness variation of shells

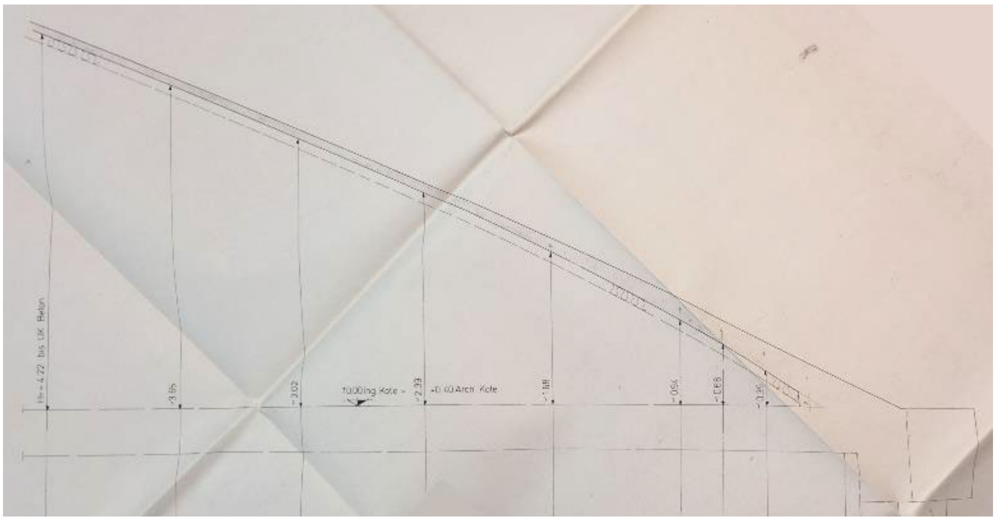


Figure 13 Diagonal cross section of the Heimberg swimming pool (Source: gta Archive / ETH Zurich)

At the supports only the translational degrees of freedom have been constrained. It could be argued that the supports behave as fixed, since there is a stiff floor and reinforcement present. This would have an effect on the structural behaviour - especially buckling. Since this model is the product of a hanging model it is, for now, assumed this effect is minimum due to low relative bending moments. Further studies should show what the actual effect is.

A mesh size of approx. 500 mm was implemented. The material was modelled as concrete with a Young's modulus of 20000 N/mm^2, Poisson's ratio of 0.2 and specific weight of 2500 kg/m^3.

For this paper, only one load case has applied, namely an uniformly distributed load of 1 kN/m^2 in negative z-direction (downwards)

3. Stress and buckling ratios

The performance of the shell is studied by quantifying membrane and buckling behaviour of the shells using linear elastic analysis. The stress ratios are determined based on internal forces. And the critical buckling load ratio (λ-value) is determined for buckling.

3.1. Stress ratios

For a curved surface structure, it is necessary to evaluate if the structure performs as a shell or a plate. Stress ratios can be used to evaluate the so-called shell behaviour. The stress ratio is defined as the ratio between axial stress caused by normal forces and total stress caused by normal forces and bending moments. Similar calculation have been described by Q. Li [11]. As shown in Figure 15, if the ratio approaches 100%, on the horizontal axis, it indicates membrane behaviour, while a ratio closer to 0% indicates more plate like bending behaviour. The ratio -100% is here considered to indicate shell behaviour since it is in compression.

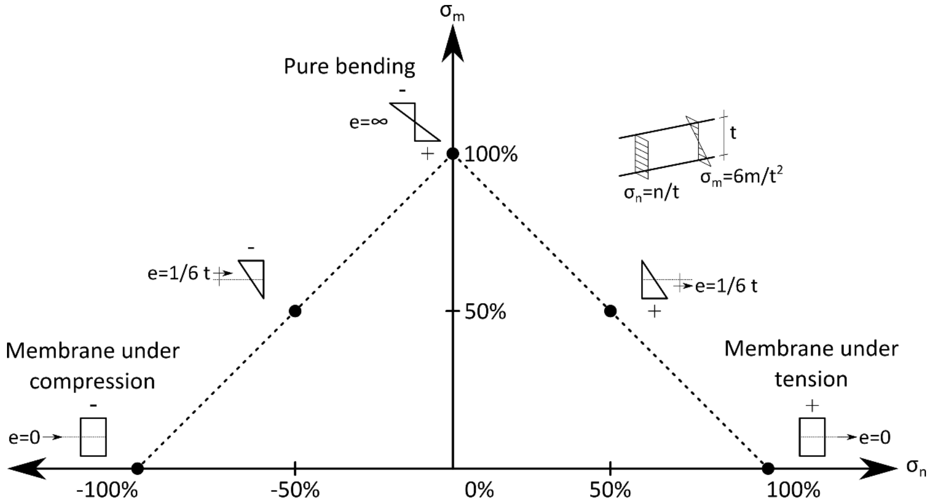


Figure 14 Stress ratio graph for stress due to normal force and bending [12]

These ratios can be found for various directions. In this article, they have been determined for the two directions of the principal normal forces. Based on the membrane forces n_{xx}, n_{yy} and n_{xy}, the principal directions α_0 and $\alpha_0 + \pi/2$ can be found. Based on the internal forces the stress ratios can be expressed as in Equations 1 to 4. R_1 denotes the ratio in the direction of the first principal normal force, and R_2 denotes that in the direction of the second principal normal force. For each point in the shell the equations describe two coordinates in Figure 15. Equations 1 and 2 together describe a coordinate for the first principal direction. Equations 3 and 4 together describe a coordinate for the second principal direction. The results describe the shell behaviour of the structure. Note that the bending moments in Eq. 2 and 4 are in absolute value. Therefore, the sign of the bending moment is neglected and the figure becomes easier to read.

$$R_{1;n} = \frac{n_1}{\frac{6|m(\alpha_0)|}{t} + |n_1|} \times 100\% \quad (1)$$

$$R_{1;m} = \frac{|m(\alpha_0)|}{\frac{6|m(\alpha_0)|}{t} + |n_1|} \times 100\% \quad (2)$$

$$R_{2;n} = \frac{n_2}{\frac{6|m(\alpha_0 + \pi/2)|}{t} + |n_2|} \times 100\% \quad (3)$$

$$R_{2;m} = \frac{|m(\alpha_0 + \pi/2)|}{\frac{6|m(\alpha_0 + \pi/2)|}{t} + |n_2|} \times 100\% \quad (4)$$

Here, n_1 and n_2 indicate the first and second principal normal forces of the shell element, $m(\alpha_0)$ and $m(\alpha_{0+\pi/2})$ denote its bending moments in the directions of the two normal forces, α_0 is the angle between the direction of the first normal force and the x-axis of the element coordinate system, and t means the thickness of the element.

3.1. Buckling

Buckling is studied using a Structural stability Analysis. Also called Euler Stability Analysis and results in multiple critical buckling load ratios (λ). This value is a multiplier for a specific load to the point where the shell loses its load carrying capacity. The results yield multiple values for one analysis. The lowest value is the first occurring buckling mode. In Diana FEA this is implemented as in [13].

4. Results

The results of the finite element modeling and further processing of the data is now presented.

4.1 Stress ratios

The result for the stress ration have been obtained by using mesh data and tabulated results from Diana FEA and calculating the area and stress ratios of each mesh element. Therefore the results can be expressed as percentage of the total area in the figures below.

Figure 16 shows the stress ratios for the first principle direction of the membrane force. It can be seen that, for both models, more than 50 percent of the shell area (in white) is in tension in the middle surface. In both models, this membrane force is about 18% of the largest compression force in the shell. It shows that the design method using a hanging membrane does not result in a pure compression shell in all directions. It should be noted that stress ratios are a relative measure and therefore this does not necessary means these stresses are large or lead to problems. But they do show reinforcement in the concrete shell is a necessity. At the center of model 1 the stress ratio is between 0% and 75% membrane action in compression. The stresses due to membrane forces become so low that even small bending moments lead to a relative higher contribution of the total stress.

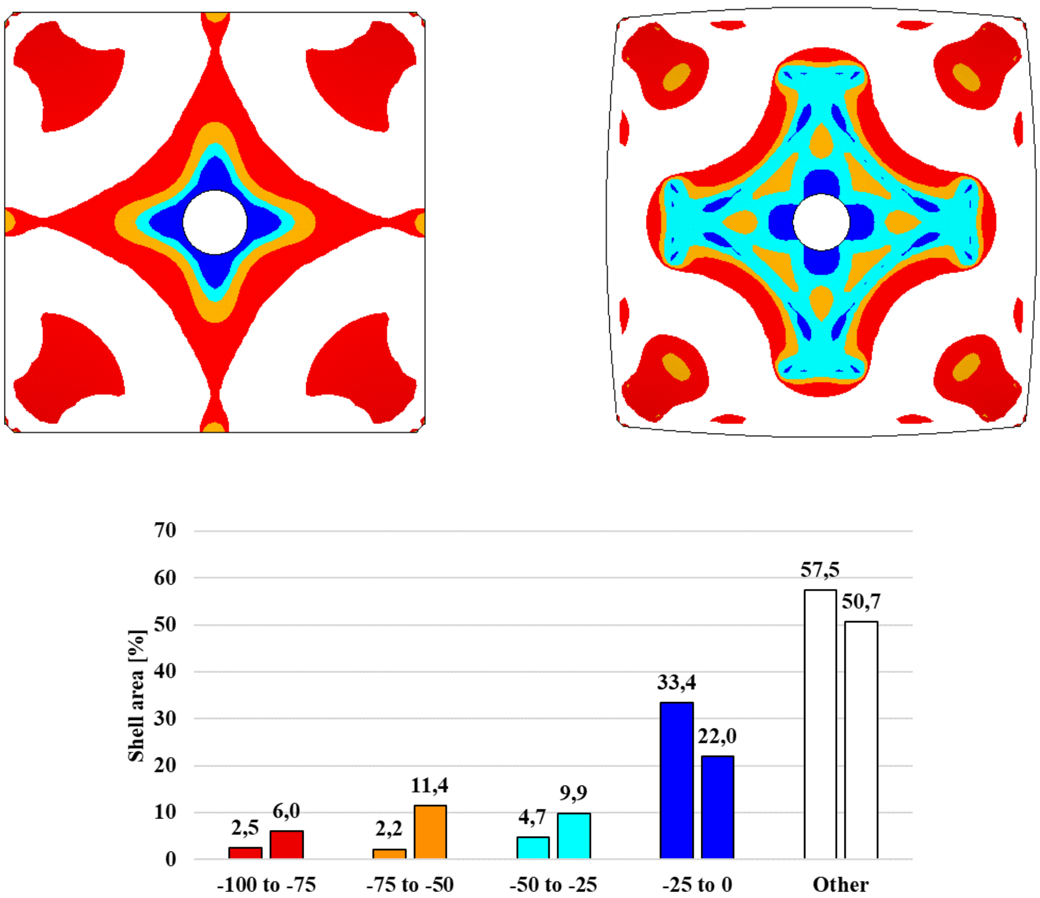
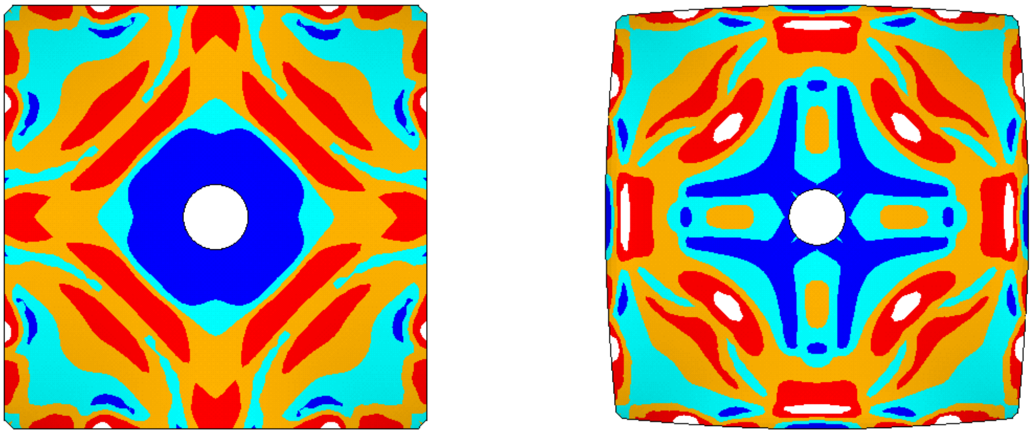


Figure 15 Stress area ratio $R_{1;n}$ for Model 1 (left) and Model 2 (right)

The second stress area ratio is easier to relate to since it is in the second principle direction of the membrane force, which often is compression. Results are much more in favour of membrane behaviour in compression. 39% and 43% of the shell are of respectively model 1 and 2 is in pure compression. These areas are mainly located in the same place where $R_{1;n}$ is showing tensile membrane action. Model 2 shows approximately 4% more membrane action in tension. These white areas stand out since they are in the middle of areas in pure tension. Additionally, these white areas overlap with the white area in $R_{1;n}$. Meaning that at these position, in both directions, there is no compression of the middle surface at all. For this specific load case, the difference in shape between model 1 and 2, has resulted in slightly less shell behaviour.



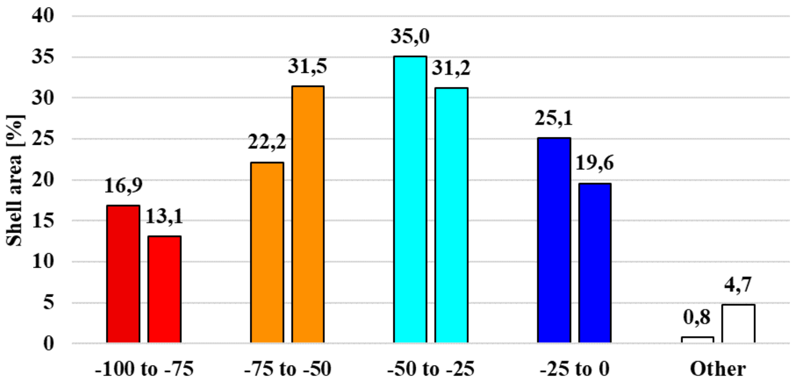


Figure 16 Stress area ratio $R_{2;n}$ for Model 1 (left) and Model 2 (right)

4.2 Buckling

The results of buckling analysis show whether the resistance against buckling has changed by changing the shape. Table 2 show the critical buckling load ratios. The resistance of model has increased by 17%.

Model 1	Model 2	Difference
5.8	6.8	+17%

Table 2 Critical buckling load factors (λ)

6. Conclusions

The turned-up curved edges are needed to transfer the load away from the edge but primarily to provide sufficient (bending) stiffness to resist asymmetric loading and buckling. When a shell's edge losses its curved shape it van induce buckling, similar to in-extensional deformation of a shell when a support has a settlement. As a result of curvature change perpendicular to the edge of the shell between the surface and the turned-up curved edge bending will occur. The stresses due to bending are small and justify the cost for the stiffening effect of curving the edges upwards. This shows the need for allowing bending is shell structures. Another Isler shell with a square plan is the bubble shell, but with a different form-finding method to the swimming pool and which has pre-stress to deal with the bending [14].

Acknowledgements

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