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Optimal Segmentation of Glass Shell Structures

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Monolithic glass shells can be constructed in limited sizes. Segmented shells allow coverage of larger spans. Three shell systems - spherical dome, cylindrical roof and hyperbolic paraboloid were segmented using four different curved glass segment shapes – square, diamond (or pie for dome), hexagon and hexalock. Three joint materials were analysed-glass (resulting in a monolithic glass shell), silicone (soft adhesive) and epoxy (hard adhesive). A Reissner-Mindlin finite element was used in ANSYS to discretize the modelled geometry. The boundary conditions were setup keeping in mind the favourable membrane behaviour of shell structures. It was found out that glass segment shape and joint stiffness has an influence on the shell behaviour. Optimal shapes show similar behaviour in comparison to monolithic glass shell. Others show a significant increase in the deflection and bending moment values which is unwanted. The in-plane membrane forces remain unaffected and thus are found to be independent of glass segment shape and joint stiffness.

Keywords: Glass, Shell, Segment, Joint, Optimal

1. Introduction

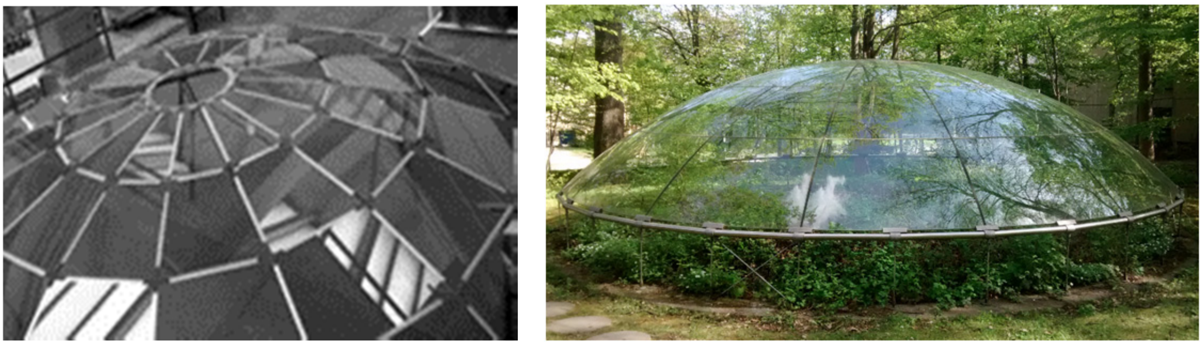
1.1. Overview

Shell structures are intriguing, efficient and moody. Glass is fascinating, underused structurally and brittle. Combining these two results in a very efficient structure – a glass shell. During shell construction, it is not feasible to have a large continuous glass surface as glass can be produced in limited sizes and curvature. Thus, assembly of individual curved glass segments or panes is necessary to construct a larger size shell. The influence of glass segment shape and joint stiffness in segmented shells is not yet well covered by research. This Master thesis work, completed within a strict time frame of six months, is an attempt to answer these questions.

1.2. Earlier Studies

In 2002, designers at TU Delft built a structural glass dome using flat glass segments; see figure 1a. A linear joint system was used with free edges to allow for tolerances. The joint system is composed of aluminium strips glued onto the glass edges using a thick flexible adhesive. The aluminium strips are clamped together using two more strips and very small bolts (Veer et al. 2003).

Lucio Blandini had the idea of constructing a frameless glass dome using doubly curved glass segments and adhesive joints without any discrete metallic clamping systems. This research project was undertaken at the Institute for Lightweight Structures and Conceptual Design, University of Stuttgart, Germany. The end result of this research was a built prototype in the year 2004; see figure 1b. It is a spherical calotte with a span of 8.5 meter, curvature radius of 6 m and 10 mm thick laminated glass. The width and thickness of adhesive butt joint is 10 mm. The prototype, though planned as a temporary structure, has stood for ten years under the action of wind, symmetrical and asymmetrical snow loadings (Weller et al. 2014).



a) Glass dome at TU Delft (Veer et al. 2003) b) Glass shell at ILEK, University of Stuttgart (Blandini 2005)

Fig. 1a), b) Segmented glass shells – Earlier studies

1.3. Motivation

Every natural structure has a pattern on a macro or micro level. Natural structures continuously evolve (optimisation process) and adapt to the surroundings to reach an ideal performance state (Dimcic 2011). The turtle shell is composed of regular hexagons in the centre bounded by pentagons which fuse to give a straight edge to the shell. This feature is also seen in insect wings (Foy 1982). Is the turtle shell or insect wing in an ideal performance state with the hexagon segments?

Trapezoidal shaped curved and flat glass segments were used in the glass shell at ILEK, University of Stuttgart and the glass dome at TU Delft respectively. The choice of glass segment shape in these projects was governed by cost effectiveness, ease of production and handling. Considering only the structural behaviour of shells and ignoring all other practical parameters, is the trapezoidal shape optimal?

2. Methodology

2.1. Classification of Shells

Shells are primarily classified on the basis of their Gaussian curvature. For a general shell, the Gaussian curvature could be positive, negative or zero. If the centres of curvature in both the principal directions lie on the same side of shell surface, the Gaussian curvature is positive. If the centres of curvature in both the principal directions lie on the opposite side of shell surface, the Gaussian curvature is negative. If one radius of curvature is equal to infinity, the Gaussian curvature is zero; see table 1 (Kumar 1989).

Table 1: Classification of Shells

Gaussian Curvature	Positive	Negative	Zero
Surface	Doubly curved	Doubly curved	Singly curved
Name	Synclastic	Anticlastic	Developable
Example	Sphere	Hyperbolic paraboloid	Cylinder
Developability	Non-developable	Non-developable	Developable

2.2. Analysis of Shells

There is a close analogy between trusses and shells. A truss system primarily carries the applied loads by axial tension or compression. A small part of this load is carried by the transverse shear force in the members which is related to the bending moments at joints. To make the analysis simpler, it is assumed that the joints are frictionless pins and there is no bending moment and transverse shear forces.

Shells carry applied loads by a combination of stretching and bending action. If the bending action is very small, it is convenient to use an analysis procedure similar to trusses where bending is completely ignored in calculations. It is assumed that applied load is carried only by in-plane stress resultants. This is known as membrane theory (Calladine 1989). In practice, bending moments and transverse shear forces cannot be ignored in shells which makes the analysis very complicated. Therefore, finite element analysis software package ANSYS Mechanical Parametric Design Language (MAPDL) has been used for the analysis.

2.3. Material Properties and Loading

The segmented shells comprise of glass segments joined with glass (resulting in a monolithic glass shell), silicone (soft adhesive) and epoxy (hard adhesive) joints. All materials are assumed to be linearly elastic and isotropic. The material properties are listed in table 2 (Dillard 2010). The 3 shell systems are subjected to self-weight only.

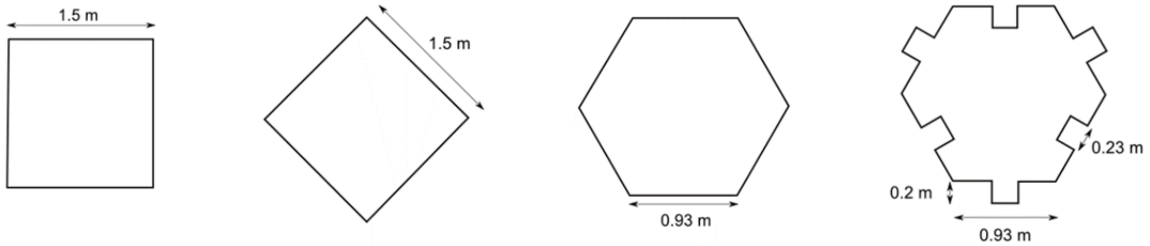
Table 2: Glass and Adhesive Properties

Material	Density [kg/m^3]	Young’s modulus [MPa]	Poisson’s ratio	Shear modulus [MPa]
Glass	2500	70000	0.23	28455
Epoxy	1100	1500	0.35	556
Silicone	1100	10	0.46	3.4

2.4. Geometry Modelling

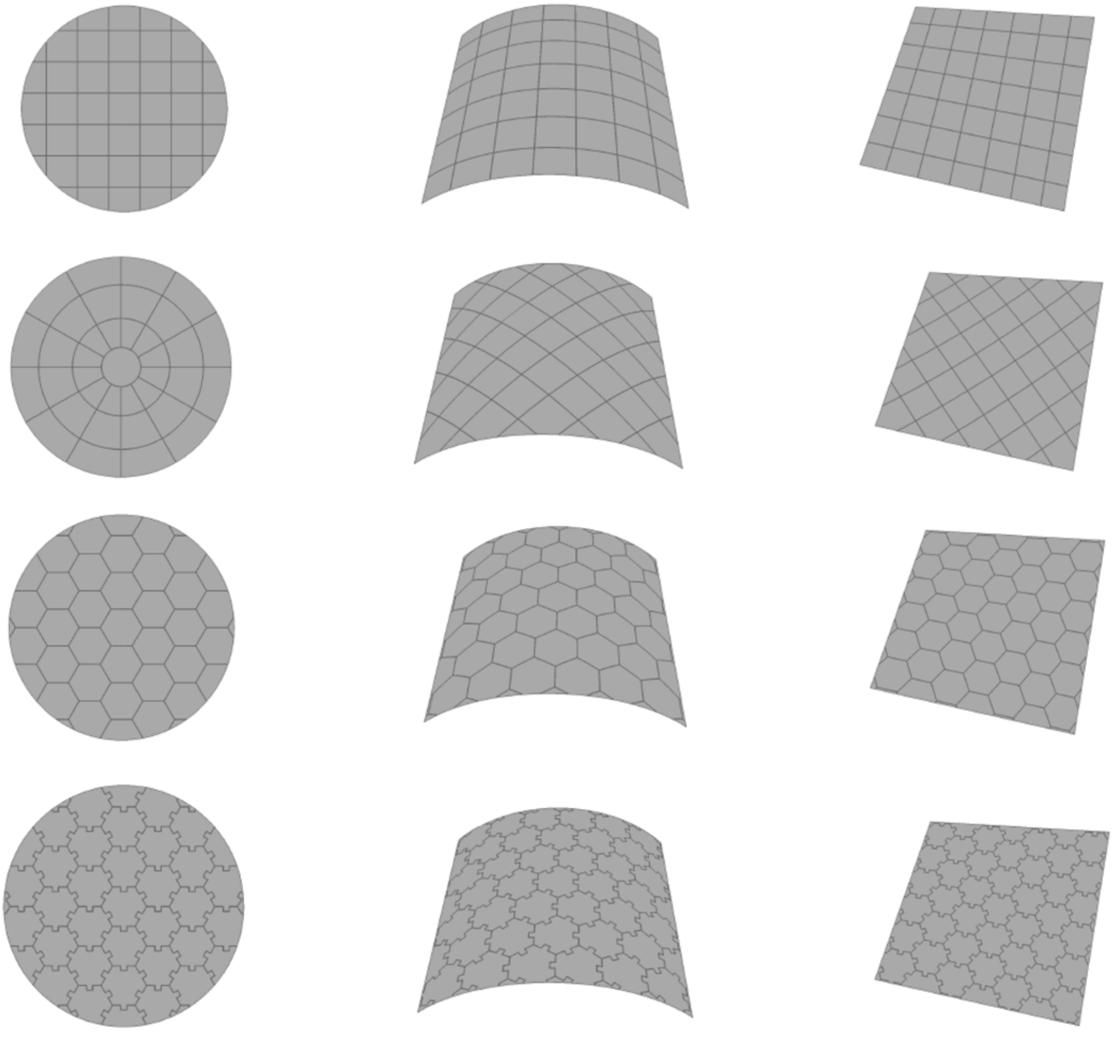
The goal was to model three segmented shell systems - spherical dome, cylindrical roof (or barrel) and hyperbolic paraboloid (or hypar). These shells are 10 m by 10 m in plan, have a rise of 2 m and joint width of 20 mm. Each of these have four different glass segment shapes – square, diamond, hexagon and hexalock; see figure 2 and 3. For spherical dome, the pie segmentation pattern was modelled instead of diamond pattern. In total, 36 segmented shells (3 shells systems x 4 segment shapes x 3 joints) were analysed in ANSYS. The size of glass pane can influence the membrane behaviour of shell as a very big segments can develop high local bending stresses. This was taken into consideration while choosing the segment size. The planar surface area of each glass segment (square, diamond, hexagon and hexalock) is 2.25 m^2. The joints between glass segments should not be continued around the vertices (Aanhaanen 2008). This was implemented in the geometry model to allow for tolerances.

The geometry modelling of segmented shells was a challenging task. Various approaches were tried to create a working finite element model. CAD tools like Rhinoceros and Grasshopper proved to be the most effective options. The required geometry for different segmented shells was created in Rhinoceros and exported to 'SolidWorks surfaces type IGES' file format with a tight tolerance of 0.001 mm. This file was imported in DesignModeler which is a part of ANSYS Workbench platform. The ANSYS Neutral Format (.anf) file was exported using DesignModeler. This file format was then imported into MAPDL and it worked without any data loss.



a) Square b) Diamond c) Hexagon d) Hexalock

Fig. 2a), b), c) and d) Glass segment shapes



a) Dome b) Barrel c) Hypar

Fig. 3a), b) and c) Segmented glass shells – Dome, Barrel and Hypar

2.5. Finite Element Modelling

Various types of shell finite elements are available in the ANSYS element library. SHELL181 element was used for the analysis. It is a four noded shear deformable element with membrane and bending stiffness. It has six degrees of freedom at each node: three in translation and three in rotation. SHELL181 is based on first order shear-deformation theory which is usually referred to as Reissner-Mindlin shell theory (ANSYS 2009). The eight element stress resultants with directions are shown in figure 4. The red dashed lines are drawn to avoid confusion about the moment rotation axis.

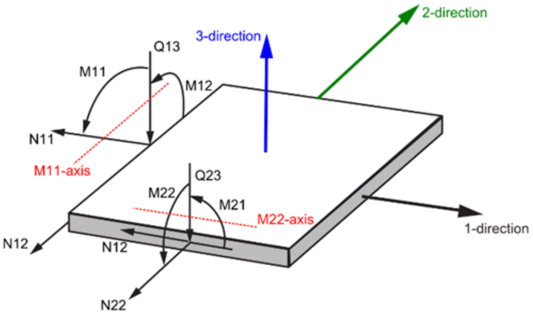
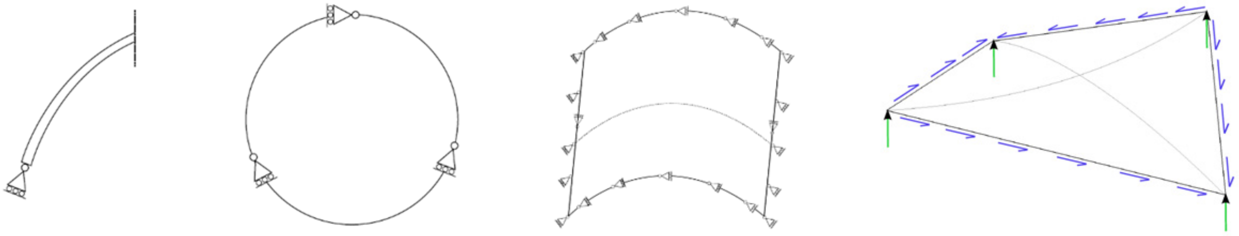


Fig. 4 SHELL181 element technology (ANSYS 2009)

Mesh sensitivity analysis was done and element size of 50 mm was chosen. In dome, tangential hinge support to mid-surface were provided along with 3 additional hinge supports along the edge to avoid rigid body modes. In barrel, tangential hinge support to mid-surface were provided along the longitudinal edges and circumferential hinge supports were provide along the traverses. In hypar, hinge supports were provided along the edges to resist edge shear force and 4 vertical hinge supports were provided at corners. All the boundary conditions were setup keeping in mind the favourable ‘membrane behaviour’ of shells and solution convergence in ANSYS; see figure 5. Before using the finite element model results to draw any conclusions, it was important to verify them. FE membrane stress values in monolithic glass dome, barrel and hypar were verified using analytical formulas.



a) Dome b) Barrel c) Hypar

Fig. 5a), b) and c) Boundary conditions of shell systems

3. Results

3.1. Overview

Selected analysis results in the form of graphs are presented and discussed in the following sections. In the graph legend; ‘glass/monolithic’ refers to the monolithic glass shell. Results for monolithic glass shell are set as a reference and results for various segmented shells are compared to it. Complete analysis results are summarized in table 3.

3.2. Dome

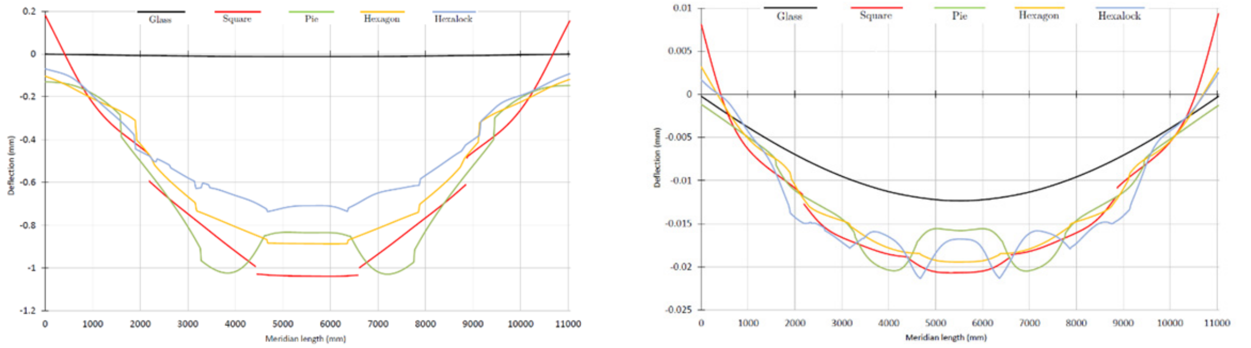
See figure 6 for segmented dome results. The hexagon segments with epoxy joint show minimum deflection. For silicone joint, the hexalock segments show the least deflection followed by hexagon segments. The meridian and hoop direction in-plane forces are minimum when the hexagon segments are used with epoxy and silicone joints. The hexagon segments show the least bending moments in the meridian direction with both joint types. In the hoop direction, pie segments show the least bending moments with both joint types.

These results indicate that the hexagon segmentation is optimal for domes. The in-plane forces are independent of the joint stiffness. Deflection and bending moments are dependent on joint stiffness.

3.3. Barrel

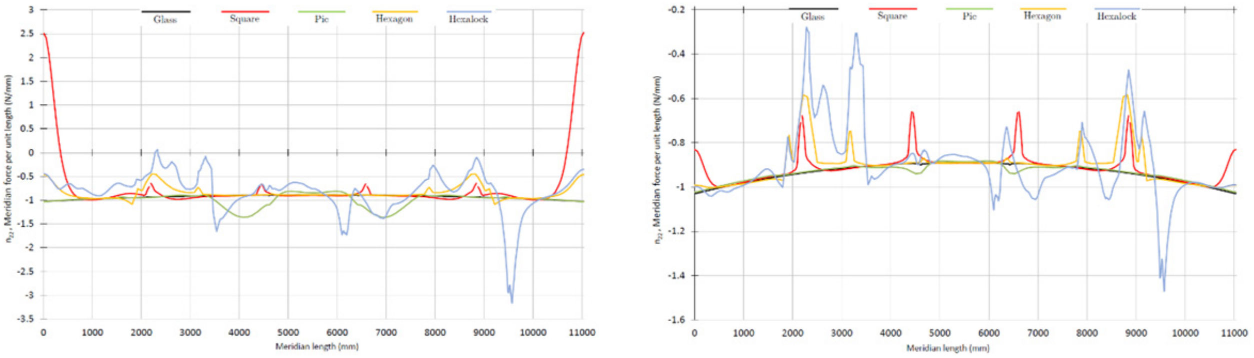
See figure 7 for segmented barrel results. The square segments with epoxy joint show minimum deflection. For silicone joint, the hexalock segments show minimum deflection. The longitudinal and transversal in-plane forces are least when the square segments are used with epoxy and silicone joints. The square segments show the least bending moments in principal directions with both joint types. In transverse direction, the bending moments are not affected by joint stiffness when square segments are used. The same is not true for bending moments in the longitudinal direction.

These results indicate that the square segmentation is optimal for barrel. The transverse in-plane forces do not get affected by joint stiffness. The longitudinal in-planes forces are double for silicone joint in comparison to epoxy joint. The deflection and bending moment results are dependent on joint stiffness.



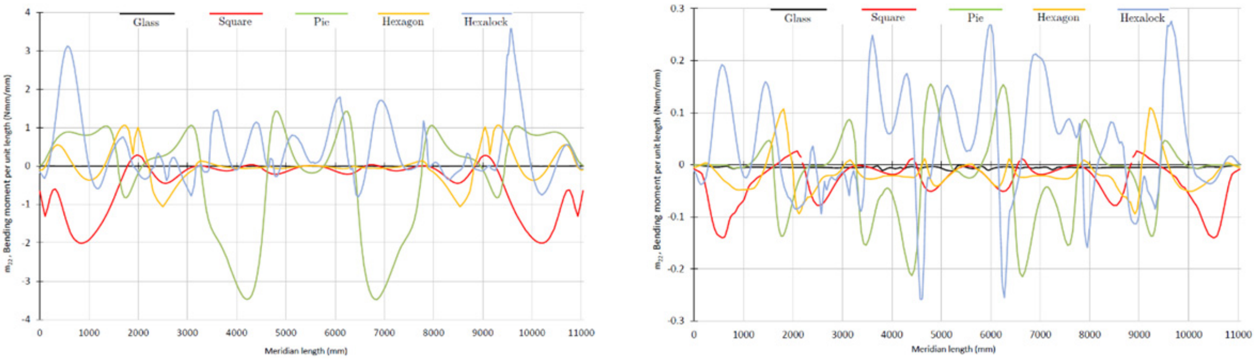
a) Deflection with silicone joint

b) Deflection with epoxy joint



c) Meridional in-plane force with silicone joint

d) Meridional in-plane force with epoxy joint



e) Meridional bending moment with silicone joint

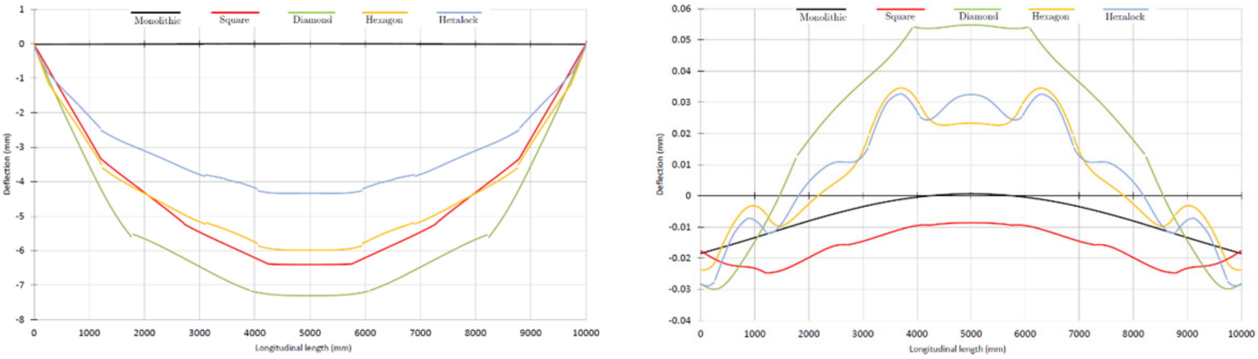
f) Meridional bending moment with epoxy joint

Fig. 6 Results for segmented domes

3.4. Hypar

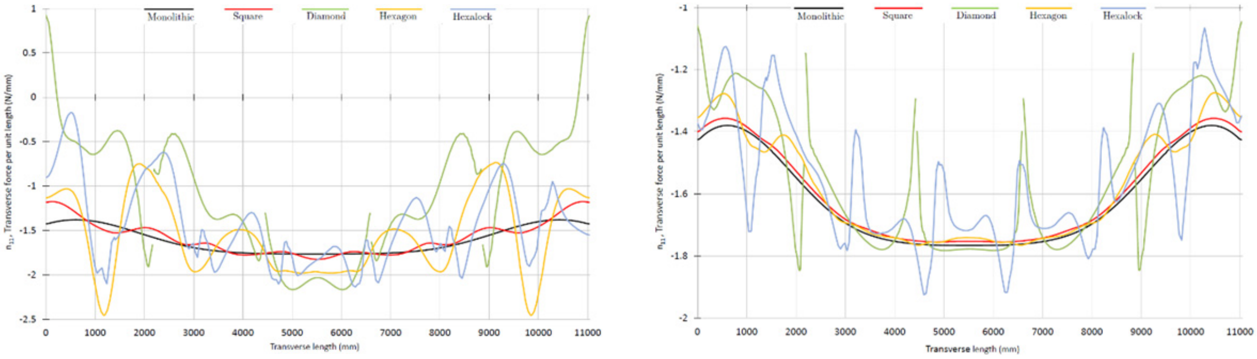
See figure 8 and 9 for segmented hypar results. The diamond and hexalock segments with epoxy joint show the least deflection. For silicone joint, the hexalock segments show the least deflection. The square segments show very high deflections compared to other segmentation patterns. The in-plane shear forces are minimum when square segments are used with both joint types. But due to very high deflections, the square segments were ruled out and the next best option was the diamond segments. In the in-plane shear force plot with epoxy joint, the hexalock segments showed very high force values and was removed from the graph plot to have a better comparison of other segment results. The bending moments remain unaffected when the diamond segments are used with epoxy joint.

These results indicate that the diamond segmentation is optimal for hypar. The in-plane forces and bending moments are independent of the joint stiffness. Deflection values are dependent on the joint stiffness.



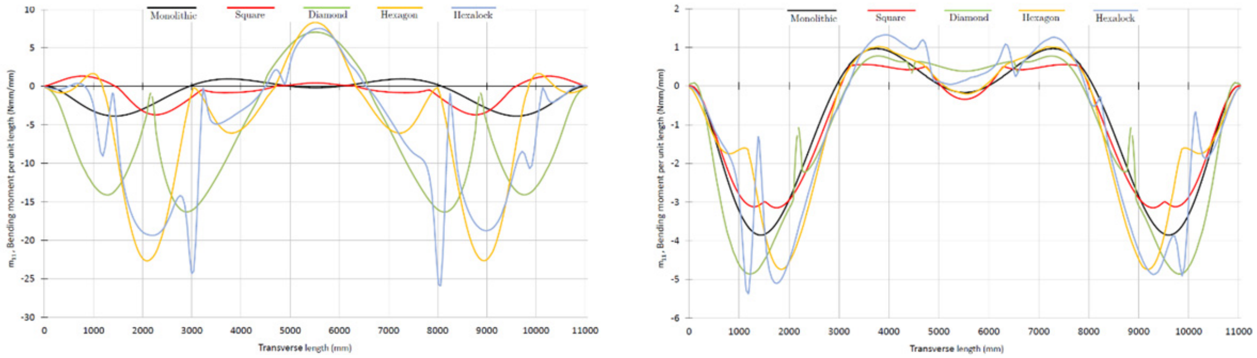
a) Deflection values along longitudinal path with silicone joint

b) Deflection values along longitudinal path with epoxy joint



c) Transverse in-plane force with silicone joint

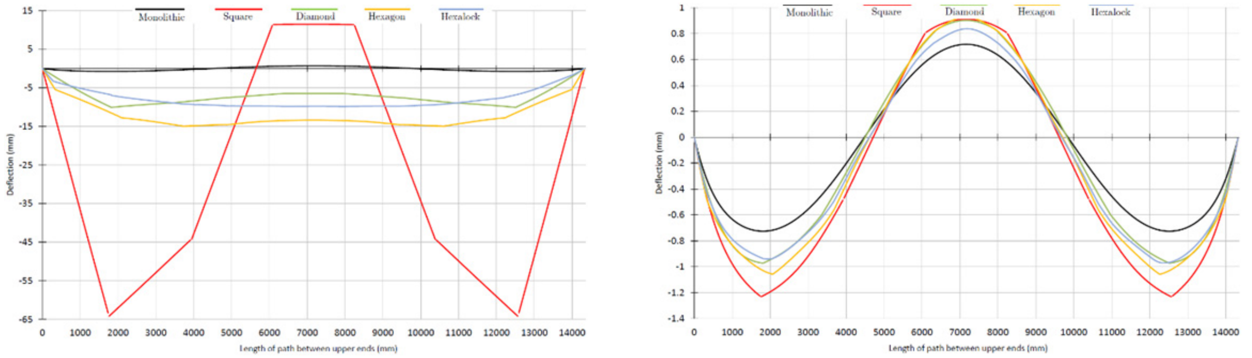
d) Transverse in-plane force with epoxy joint



e) Transverse bending moment with silicone joint

f) Transverse bending moment with epoxy joint

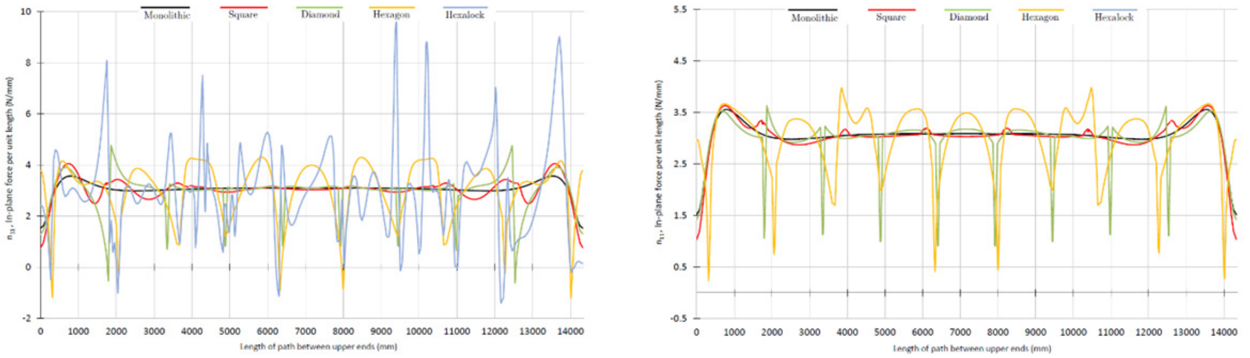
Fig. 7 Results for segmented barrels



a) Deflection with silicone joint

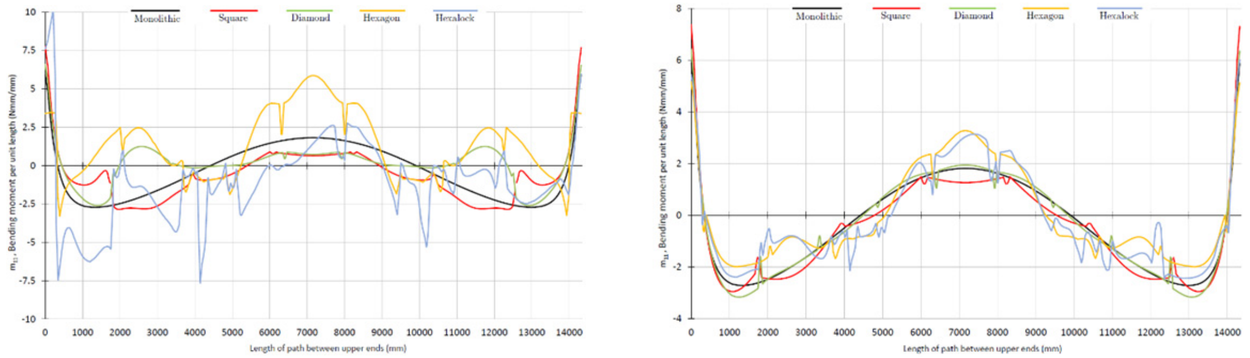
b) Deflection with epoxy joint

Fig. 8 Results for segmented hypar



c) In-plane shear force with silicone joint

d) In-plane shear force with epoxy joint



e) Bending moment with silicone joint

f) Bending moment with epoxy joint

Fig. 9 Results for segmented hypar

3.5. Summary

Table 3 shows the results for monolithic glass shell and optimal results for segmented shell with silicone (soft adhesive) and epoxy (hard adhesive) joints. The ‘increase factor’ is the ratio of segmented shell result to the monolithic glass shell result.

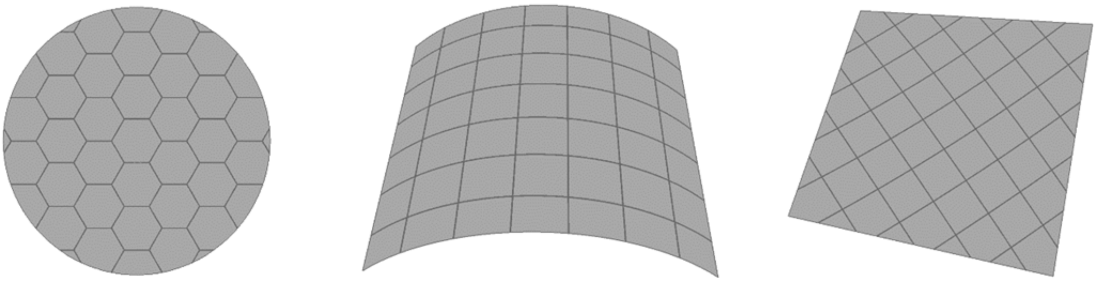
Table 3: Summary of Results

Shell type	Parameter	Optimal pattern with silicone (soft) joint	Increase factor with soft joint	Optimal pattern with epoxy (hard) joint	Increase factor with hard joint
Dome	Deflection	Hexalock	60	Hexagon	1.6
	In-plane force in meridian direction	Hexagon	1	Hexagon	1
	In-plane force in hoop direction	Hexagon	1	Hexagon	1
	Bending moment in meridian direction	Hexagon	87	Hexagon	9
	Bending moment in hoop direction	Pie	40	Pie	3.6
Barrel	Deflection along longitudinal path plot	Hexalock	238	Square	1.3
	Deflection along transverse path plot	Hexalock	20	Square	1.4
	In-plane force in longitudinal direction	Square	2.1	Square	1
	In-plane force in transverse direction	Square	1	Square	1
	Bending moment in longitudinal direction	Square	79	Square	8.3
	Bending moment in transverse direction	Square	1	Square	0.8
Hypar	Deflection	Hexalock	13.6	Diamond	1.3
	In-plane shear forces	Square	1.1	Square	1
	Bending moment	Diamond	1.1	Diamond	1

4. Conclusions

From the results it is concluded that:

- the hexagon segments are optimal for dome.
- the square segments are optimal for barrel.
- the diamond segments are optimal for hypar.
- a hard adhesive as joint material is preferable for segmented shells.
- the joint stiffness is the primary factor responsible for optimal behaviour of segmented shells. The glass segment shape is the secondary factor.
- for silicone joints, the hexalock segments show least deflection in all 3 shell systems - dome, barrel and hypar. The same is not true in case of epoxy joint.
- the in-plane membrane forces are independent of joint stiffness for all the optimally segmented shells except in the case of barrel longitudinal direction.
- the deflection and bending moment values are dependent on joint stiffness.



a) Dome - Hexagon b) Barrel - Square c) Hypar - Diamond

Fig. 10a), b) and c) Optimal segmentation of glass shell structures

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