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All-Glass Dome for Mosque in Haarlem

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The architect Fedde Reeskamp, from the 'Architectenkamer' in Haarlem had designed a mosque for the client 'Islamitische Stichting Nederland Selimiye' in Haarlem. The design consists of a blockwork mosque with a dome on top, visually apparent in silhouette of the mosque. He came with this enquiry for a dome to Octatube. The contrast between the solid building block-shape and the dome on top led to the suggestion to have the dome made in glass, out of its extreme contrast. Octatube designed a self-supporting dome of solely insulated glass panels, without any frame or structure. Thanks to a hidden tensile system with corner joints, the complete dome is a reliable structure of glass and tensile spokes.

Keywords: Glass, Dome, Facet

1. Introduction

In 2002 research fellow Jan Wurms, at the time PhD student at Aachen, joined the TU Delft for half a year to develop an all-glass dome prototype with students in the Chair of Product Development. He later would publish his dissertation in Aachen on 'Glass structures' [ref.1]. The challenge was to make a load carrying structure of glass panels, without a metal frame or a metal structure. The glass panels themselves would have to carry the dead load plus external loadings. The design considerations between Jan Wurms and Mick Eekhout consisted of different models of a scale 1 to 4 dome: 3 to 4 meter diameter span as the prototype, in reality the target was a 12 m clear span self supporting dome.

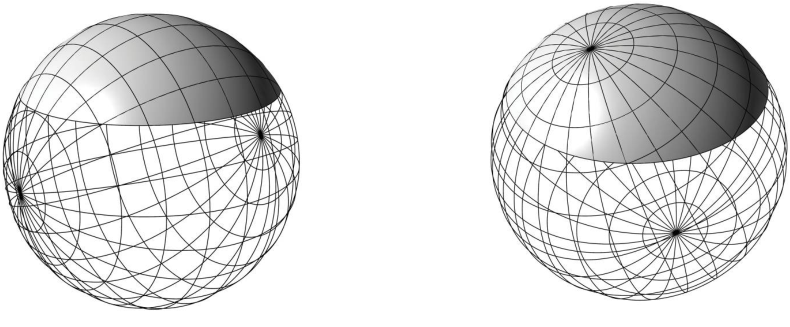

Figure 1: Examples of the design proposals by Mick Eekhout.

The prototype was developed in the Laboratory for Product Development by Jan Wurm, the staff and a group of 4th year Building Technology students. The structure consisted of a circular ring on 3 stable steel legs. The ring would ensure the stable fixing of the lowest panels, so that the ring forces could be accommodated at the ring perimeter of the dome. The panels themselves were produced as single glass panels of 6 mm thick, fully tempered. The panels were trapezoidal in form and were to be connected with demountable connections as the dome was foreseen to be erected and dismantled a few times. The dome was built up in the factory of Octatube (sponsor for the steelwork), dismantled and assembled on the outside of the Laboratory of Building technology after it moved to the former building of Bouwkunde at the Berlageweg. It was demounted once for a Building exhibition in Utrecht, where it functioned as the research umbrella for TU Building faculties. See figure 2.

Figure 2: The all-glass dome outside of the former Bouwkunde building.

The connections were made of small stainless steel strips provided with small screws, see details in figure 3. The idea of this model was a scale prototype 1 to 3 or 4. A more safe solution for users would have been realised when using laminated glass, and by doing so the safety for using the dome as a roof for a students' beer bar would have increased. So the prototype was actually not very safe in its use. The end of her technical service life was 13 May 2008, when the Big Fire of Bouwkunde destroyed the building and the falling debris ensured that nothing was left of this prototype, except photographs and descriptions. A correct scale model would have to be executed in insulated, laminated, pre-stressed glass panels with a thickness of 40 to 50 mm. So the actual thickness of 6 mm glass was twice as slender as the real scale reality.

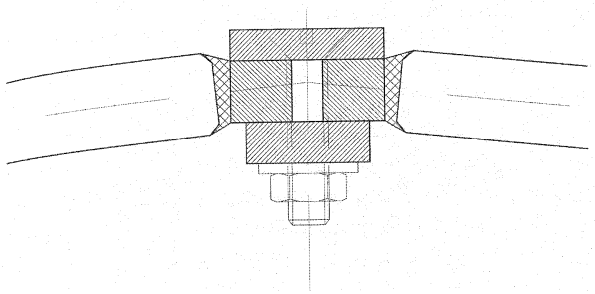

Figure 3: Details of the connections of Jan Wurms dome (glass thickness 6 mm).

2. Request for an eight meter span dome in Haarlem

In Islamic architecture a glass dome is not often the case. Usually the domes are made of bricks (traditional) or concrete. In 1988 the author designed a counter proposal for the State Mosque of Malaysia, which was published in his dissertation [ref. 2].

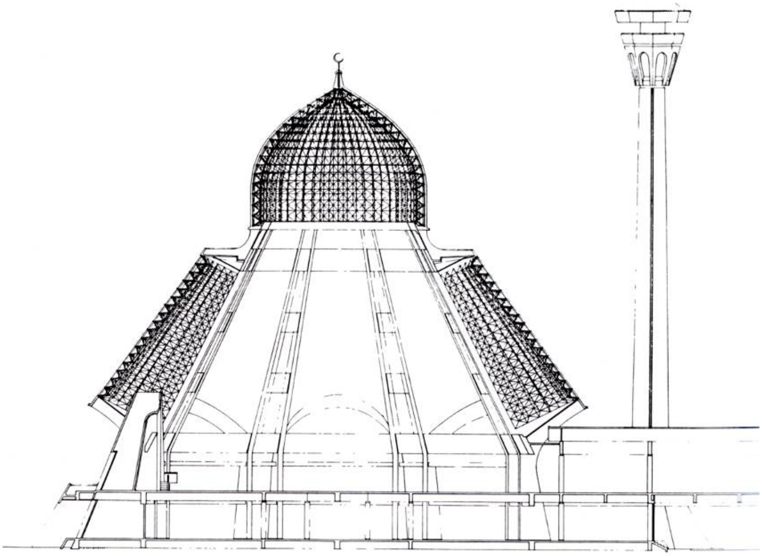

Figure 4: Design drawing by Mick Eekhout of the State Mosque in Kuala Lumpur in 1988, not realised.

Most domes are either closed or have small windows below the dome. They are usually provided with calligraphy on the inside. In glass this calligraphy could have been the case, but was not the preference of the architect. Neither did Octatube as the structural designing engineer want to make an experimental dome project even more complicated by printing calligraphy on the inside. The design was made in 2005. State of the art was only a few years after the single glass dome of Jan Wurm. The structural idea was similar to the 4 m diameter dome prototype: self load-carrying structure, made entirely of double glass panels with only mechanical connectors at the corners of the glass panels. The geometry chosen was a 5 pointed network geometry in 3 rings and 2 different panel sizes. The triangular geometry was chosen out of reasons of geometric stability and visual crystalline outlook. In reflection of this: it would not make sense to keep to the triangulation of glass panels, as the shell surface in glass is continuous and the subdivision in triangles or conical glass panels does not change the form and flow of forces much. So in principle this should also work with other types of glass panel subdivisions. Triangulation is very inefficient in material sustainability.

Already before the initiative for the all-glass dome reached Octatube, Fedde Reeskamp had thoroughly been studying the great classic examples of Mosque-architecture. Although the appearance of the Selimiye Mosque in Haarlem is quite modern, underlying principles for its design were historic references of geometry, symbolism and decoration. This design approach was to be continued in the glass dome. Hence it was the 'diamond shaped' triangulated distribution in stead of any other distribution that convinced the architect and, even more important, the client to commit themselves to the realisation of ' their' dome by this all-glass experiment. Depending of the sizes of the glass panels the 3-frequency was chosen, see Figure 5.

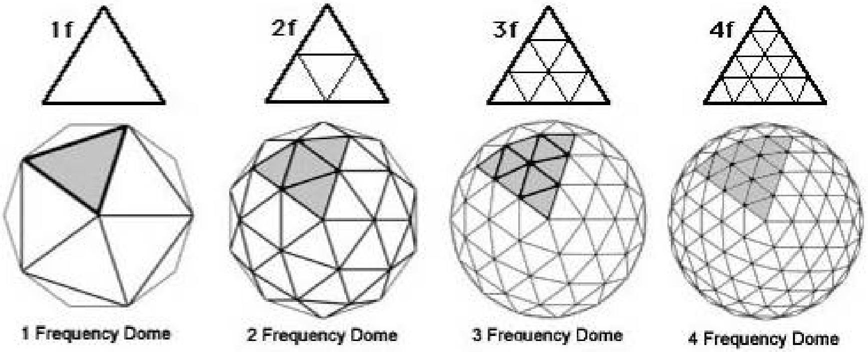

Figure 5: Different subdivisions of triangulated geodesic all-glass domes.

3. Design and Development Process of the Connections

Actually determining the subdivision and lay-out of the glass dome, was more easy than the development of the connections. The dome with its triangular division consists of half a sphere, being 8 meters in diameter and 4 meters in height. In contrast with the preseding prototype project by Jan Wurm et al, this shape is not a perfect structural shape with a load transfer by only compression. Even for a dead load situation, significant tensile forces occur within the dome. For any other way of asymmetrical loading these tensile forces will only increase. The connection between the glass panel therefore had to be designed for tension and pressure force as well. Among the first analysed ideas for a connection was to create holes in or glue metal connectors to the glass laminated panels and attaching one another by means of steel elements. Possibly one piece connects more holes/glued connectors at the same time. Whenever such a connection is loaded with a centric force within the plane of the glass it can transfer considerable forces, all though still not very large. Loading the connection with an extra bending moment caused by eccentric load introduction, would minimize the load bearing capacity. Because the glass is insulated, a centrically loaded connection is difficult to realise. The connection needs to go through the inner and outer pane. The latter is (too) vulnerable for such detailing causing panel leakage sooner or later. Changing a panel because of a broken glass pane is not a very easy job, so all together this type of connection seemed not a desirable solution.

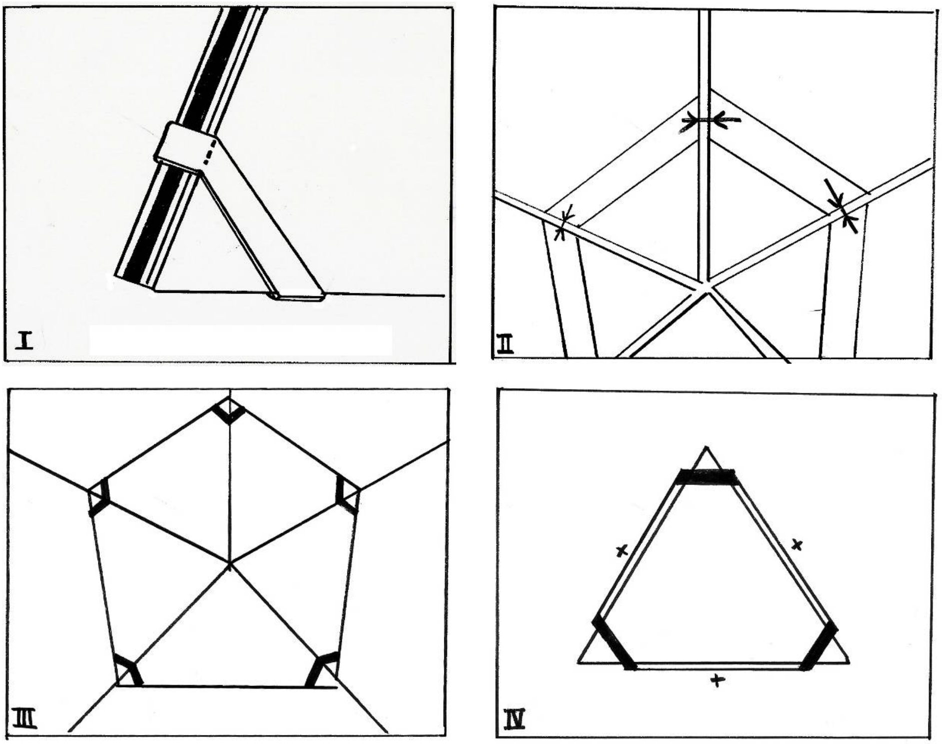

Figure 6: Steps of development of socket connection.

A completely different approach was followed in the next idea. Step by step this approach let to the final connection design. See fig.6. The problem of the transfer of large forces was tackled by using a socket (Sketch I) to be placed over the corners of the triangle. Adjacent sockets of neighbour glass panels are connected mechanically (Sketch II). Tension force in the connection is derouted by the sockets to the other ends and introduced in the glass panels as a pressure force (Sketch III). Because of its brittle structural behaviour glass is practically unbreakable under compressive stress. The socket has a tight fit onto the edge of the glass panel, making possible a force transfer through both the inner laminated and outer single glass panel. At the same time a rather large area is used for force-introduction. All together this approach led to a connection which was far out stronger than the first idea.

As the structural behaviour of this connection was analyzed by finite element analysis of the whole structure, it showed the system was not completely stable yet. For certain types of loads on the dome, the sockets would be sliding of the corners. Among them different scenario’s of 1, 2 and 3 (structurally inactive) broken glass panels randomly spread over the dome. Still convinced of the ‘socket’-principle a network of tension rods connecting all sockets was introduced to provide for a 100% tension-compression-transfer throughout the whole dome in any direction (Sketch IV). The network was optimized to fits in the silicone joints and be invisible after the sealant between the panels was applied. As a secondary function the network of rods was used for tightening the sockets onto the corners.

4. Final design of the Pre-stressed Connection

Although the principle of the connection was agreed on from a structural point of view, regarding water resistance and ability of replacing broken panels afterward it was not perfect. A protruding socket would form an interruption of the silicone joints and thereby a possible leakage. Especially between the edge of the glass panel and the socket itself water could come through. Therefore in its final design instead of separate sockets one ring is used. (See fig.7).

The ring is only present on the inside; between each glass panel a steel strip is put upright. After placing the glass panels clamps are placed upon the upright strips. Only the strips are protruding the sealant, but the clamps on the strips are water sealed. By demounting all clamps around one panel, this panel can be replaced. Due to the change into a single-sided 'socket' the thickness of the strip and ring are large in comparison with a double sided one.

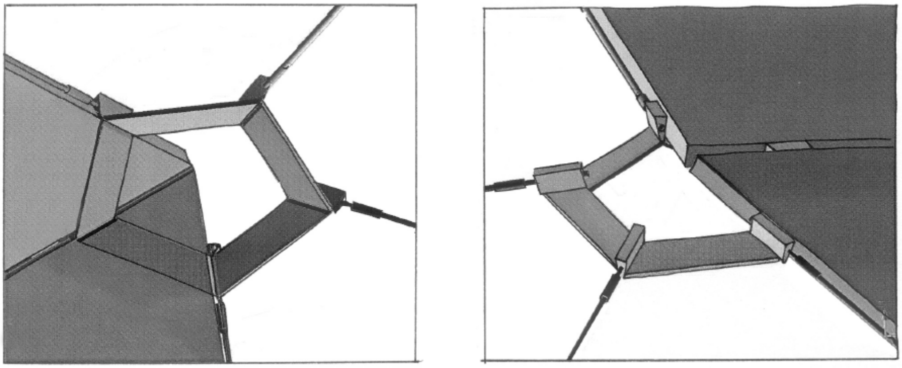

Figure 7: Single sided socket as a ring.

This is because the ring will also experience bending. Along with the introduction of the ring a well appreciated esthetical pattern appeared in the connections as another reference to geometric patterns in historic Islamic architecture. The diameter of the ring was finally chosen in such a way still enough light peered through it, avoiding the connection appearing all black.

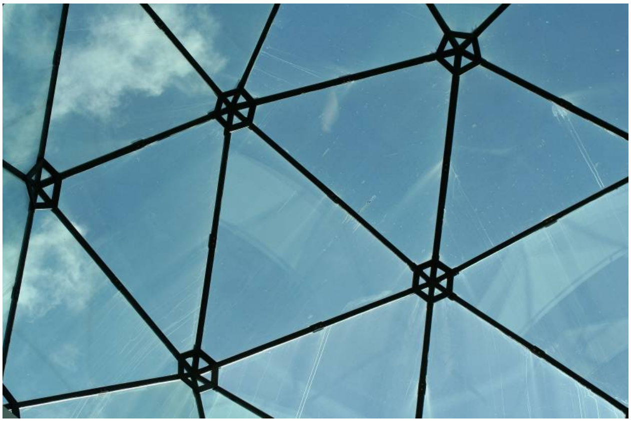

Figure 8: Open ring connection seen from the interior (Photo: Gerard Petersen).

At the base of the dome instead of complete rings, brackets in the shape of half rings on a base plate are used. All brackets are positioned onto a HEA base profile following the contours of the ten lower glass panels. The HEA base is levelled beforehand. The ten brackets are in fact the supports of the dome. Because the stiffness of the dome itself is extremely high, it is very important that the lower structure is sufficiently stiff. Otherwise one or more of the 10 supports could easily lose or minimize its bearing function, eventually resulting in a dome which will at least be supported by three supports. In the end the stiffness of the support proofed to be insufficient, causing forces in the connections about two times higher than any other load situation. Luckily the dome's position was always meant to be lifted from the top of the roof for about one meter, to assure the dome would stay visible from a distance. On site a truss ring of one meter was created in this height of one meter. Hereby the roof stiffness increased significantly and support-stiffness issue was no longer a problem.

5. Production of elements and components

Not only in architecture the phrase 'less is more' is valid. It was definitely valid for the structure of the all-glass dome. Although adding as little additional structural elements as possible, all parts were produced involving lot of time, due to the accuracy demanded. For a structure of glass panels, fitted like a puzzle and intermediate connections which have very little tolerance the production tolerances of both glass panels and steel structure were set extremely high. Because load is transferred through the sides of the glass panel, not only the external geometry of the triangle is of importance but the relative position of the 3 x 8 mm glass plates sides needs to be in a straight line. All glass plates are CAD-CAM laser cut with a high accuracy. Both additional steps of laminating and insulating adds uncertainty to the final dimensions, especially the relative position of the plates. Beforehand tolerances were a very important aspect in choosing a supplier of the glass panels. After extensive deliberations, AGC-Westland became the supplier. All important tolerances were agreed by contract and for both panel type two prototypes were made. One of them was produced within, the other outside of the set limits of tolerance. This experience was used to put even more emphasis on the manual part of the production line. Unfortunately it proved in practice impossible to produce all panels within the set goals. More than half of the panels exceeded the tolerances. Now both parties were facing a major problem. It was agreed to work out a solution together instead of simply pointing ‘the finger’. There is no use for laboratory tolerances in practice.

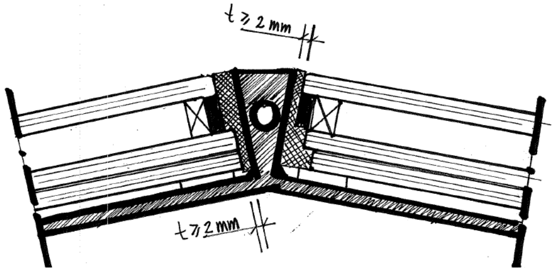

Figure 9: Adaptation of POM strips to adjust deviations from the theoretic shape

The solution was found in the elaborative job of adapting all POM-strips in between glass side and the upright steel strip in order to fit exactly. The initial joint was hereby enlarged because a mm thickness of 2 mm was maintained and all deviations add to the thickness. In the end this would result in a even more precise fitting then in the initial design. (fig.9). All deviations from the theoretic shape where measured precisely by comparing each 8 mm plate to a cad-cam steel mould. All six measured sides of each panel and corresponding POM strips are uniquely marked by a panel number and a side code A-B-C-D-E-F because they are forming an unique set. The steel structure itself did involve a small number of different pieces. It was chosen to assemble the pentagonal and hexagonal rings on a mould. Hereby assuring the most important tolerance for the rings: its symmetry, the accuracy of the radius was less important, a larger radius still fits the geometry.

Figure 10: Pentagonal Mock-up of top of the dome in plywood (scale 1:2)

6. Assembly and Installation

Again for a relative small project the assembly involved a rather complex preparation. First of all the dome is (logically) placed above an atrium, a hole in the roof , meaning no working floor was present. A scaffold was raised from the mosque praying floor beneath. Because the puzzle of glass panels demands a accurate basis for assembling and the structure is only stable until all panels are mounted a temporary substructure was needed during assembly. At the same time panels can only be mounted when the steel connecting rings are present, which ‘float in the air’ as long as panels are not present. Therefore a substructure was necessary. This substructure was integrated with the working floor and all together supported by scaffolding. The substructure did not only serve a temporary structural purpose, but at the same time provides a geometrical context to be able to position the lower support ring, and the ‘floating’ connection rings at their exact position. The floor was built in a 5-way radial beam structure, avoiding egg-shape deformation of the decagonal base of the dome. This radial set up was also used to provide in supporting poles of all connection rings. The position of the poles was vertically projected on the radial structure. Once all preparation was finished the assembly did not experience any real difficulty. The accuracy of glass-POM-steel contact was satisfying but not perfect. This was to be expected, and therefore accounted for in the structural analysis beforehand. Because of the difficulty of predicting the real force transfer in the dome the theoretical goal was to create as much redundancy in the system as possible. Finally the silicone water sealant had to applied. Merely due to the angle between the glass panels and the protruding steel and POM the joints outer dimensions are quite large. A harmonica backing rubber was used to assure enough flexibility of the joint in time. The centre hole at the 3D crossing point of the joints is inevitably the weakest spot.

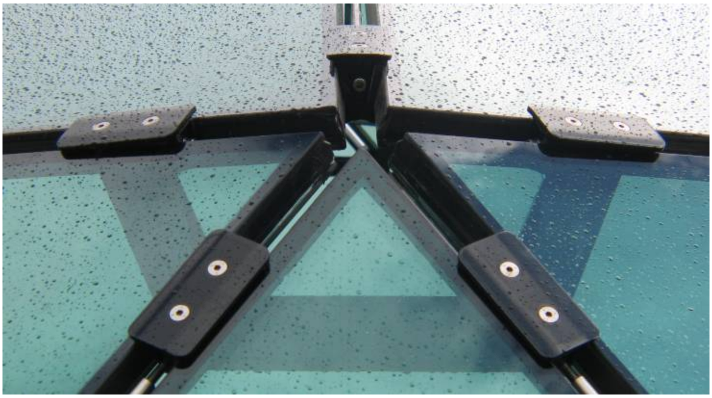

Figure 11: Crossing point of joints.

7. Conclusion

The experimental all-glass dome has been designed and developed by Octatube Engineering on the basis of a project challenge and the in-house wish to make a step forward in development of all-glass structures without window frames or supporting steel structures, from the state-of-the-art of the dome of Jan Wurm in 2003. The in-house development was facilitated by a planning time longer than usual but the planning of the mosque due to different reasons, gave a bit more time for the development. In the development time initially a prototype was built of 5 panels, the detailing was perfected and after that the engineering was worked out and the accurate production and building processes followed.

For a next project the triangulation, derived from 3 decades of experiences with space frames in tubular bars and nodes, is not necessary in a full glass dome where the stresses are distributed through the entire surface of the dome. Though the main reason for using a triangulated scheme is that the failing of one triangular plane would never jeopardize the stability of the entire dome. This is different in trapezoidal subdivisions: local instability could occur. In principle glass takes the stresses and the stresses are only concentrated along the connections. In this case of triangulation the stresses were taken at the corner points. In principle stresses can be transferred along all the edges, as was done in Jan Wurm's dome or at the corners of the panels, be it triangular or quadrangular.

Figure 12: Close –up of dome (Photo Berend van der Zanden).

Connections between the seams include the fixing of the linear connectors on the head of the glass panels. Here the glass panels, consisting of an outer and an inner pane composed of laminated plates of fully tempered glass with siliconed edge frames in between, are not likely to be produced in very accurately, that is within the laboratory tolerance of tenths of a millimetre. The alternative to take the stresses at the corners only makes use of the surfaces of the glass panels. The connectors are either inside and outside present and clamp the glass panels in between them, or fix the glass panels by means of glue between the glass surface and the metal connector. In all cases a certain shear force has to be transferred. The glued connection has the problem of prefabrication in a laboratory and has to be divided in glass saucers per glass panel corner and a hand shaped metal connector form.

The saucers can be glued in a laboratory to the glass, in which case the position of the glued connection on the glass panel can be theoretically determined. In reality all positions will have little tolerances from theory. This leads to a detailing of the hand shaped connector with compensation for the inaccuracies of the glued position. The alternative is a grip between the inner and outer connector through the sealant, causing compression forces perpendicular to the glass panel composition. The framing space will be sealed and could be filled with an internal sauced fixed inside the frame. This, however, poses high accuracies in and disruptions in the industrial production of the glass panels.

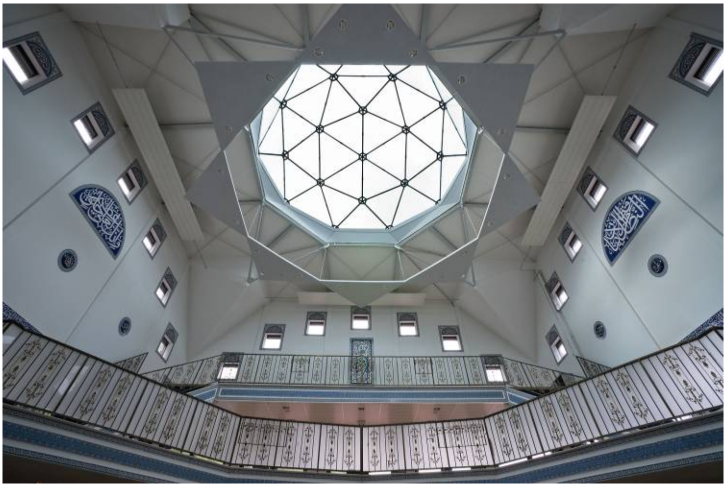

Figure 13: Interior view of the finished mosque and dome (Photo: Berend van der Zanden)

The shaping of the current pentagonal connectors will be more streamlined when a 5-fingered connector is chosen and developed where all fingers are on the outside and inside seams of a pentagonal bent between adjacent panels. The internal pre-stressed rods connecting the connectors could be made in Aramide or composites after the experiences with the INHolland façade in Delft, see the respective lecture by the same author.

Going back to the original idea of the original design proposals (see fig.1), the current state of the art would make such a design possible to realize, provided that the avoidance of local buckling due to the spatial corners in the geometry is closely analyzed. This has to do with the frequency of the subdivision, see fig. 5. When the snap-through danger if the ribs between 2 triangulated panels becomes too high, other solutions have to be included, like bending moments in the connectors. That is left for the next challenge of this 'Research by Design' quest for self load bearing glass dome structures.

8. References

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