GRP SANDWICH STRUCTURES FOR 'LIQUID DESIGN' ARCHITECTURE

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ABSTRACT
Technical design of roof and façade structures for architecture has accelerated in the last 3 decades with successive emphasis on free form stretched membrane structures, systemized metal space structures, sophisticated tensegrity structures, glass envelope constructions and load bearing glass structures. This type of architecture is computer-based rather than culture-based. Hence it cannot be regarded as a new style of architecture, as it does not have its roots in philosophy and human behavior. In a sense it is caused by technology driven interest of architects, having learned the newest generation of 3D design computer programs, capable to design complicated virtual 3D buildings that seem like they are realistic. Yet the route to reality is paved with technical experiments to produce the technical components out of which these 'Blob' buildings consist in their 3D form, often 3D-curved but in their form one-offs and non repetitive. So the contradiction is custom-made components versus the low budgets of the building industry and developing innovations in order to acquire new affordable technology. The aid of other design professions like aeronautics, ship and yacht design and industrial design is necessary in order to develop a new 'Blob' technology with the 3D forms and characteristics of the mentioned design fields, yet fitting within the modest average m^2 budgets of the building industry. This is the driving force of increasing the traditional integration of architecture with structural and industrial design, but also with aeronautical design, yacht design. This way we can develop specialised CAD/CAE, CAM/CAB procedures and special production and geodetic surveying technologies. In this case producing one-off GRP stressed skin sandwich components able to span larger spans and in a arbitrary form as to become 3D-roofs for 'Free Form' architecture. Each initial experiment in the first years of a new type of architecture is an extremely complicated process, but one where design dominates.

Keywords: Liquid Architecture, Blob technology, one-off industrialization, 3D composite components

1. INTRODUCTION
Designing and developing structural systems for architecture, including the necessary research, is the core of my personal interest. Many of the designs I have made as an architect and others as a structural designer advising an architect, have followed an incremental approach of step-by-step with ever increasing know-how and elevated insight, starting for smaller projects in the Netherlands with applications of increasing scale both in the Netherlands and abroad. The projects are performed in my company Octatube and some in my architecture office. The university offers an excellent opportunity for contemplation and to sharpen the mind with scientific design colleagues from different disciplines. Design is to tunnel results of scientific research to society. In my view the relationship between research and design are mutually indispensable.

The start of the making of the roofs of the Rabin Center has already been described in the IASS proceedings of 2004. The article 'GRP Stressed Skin Roofs for the Rabin Center' largely described the experiences of Octatube with the Israeli building industry, the initiative of the project and the design process, whereas this article focuses more on the final engineering and production. However, for the sake of completeness and chronology a short introduction to the project and therefore a summary of the relevant issues of the IASS 2004 article will be given.

In November 2002 we received the tender drawings of the Yitzhak Rabin Center, Tel Aviv, designed by Moshe Safdie Architects. The design was an extension and renovation of a former electricity plant. The tender drawings for the 3D roofs, resembling peace doves, were made by ARUP and analysed as an arbitrary steel structure with a layer of concrete. The roof cladding was left open to the contractor, yet the architect had given the preference to a seamless solution.

For months we did not give this tender much notice. The preference for a seamless solution made any prefabricated system rather difficult and the proposed structure did not seem challenging enough for us. The client and the building manager however kept reminding us of the tender date, even extending the final deadline. While struggling with an alternative technical design for the new cladding of the Atomium of Brussels (dating from 1958), TU Delft's professors Adriaan Beukers and Michel van Tooren stated in their inaugural speeches that airplanes always leak and condensate [1]. The same happened in the Atomium. Its original cladding of many pieces was designed with over 20.000 running meters of joints, of which the majority was leaking and could hardly be reached for weather tightening. This statement stimulated me to think of the Atomium as a spherical airplane and to solve the problem from there onwards. The end result was that in our proposal each of the 18m

diameter domes was to be clad with 2 x 8 spherical glass fibre reinforced polyester (GRP) segments in the form of half an orange peal, size 14m long, 8 m wide and 3m curved. This resulted in only 20% of the joint length. The joints could be detailed as the old-fashioned 'Double Improved Dutch Roof Tiles' with double internal joints that never had to be replaced or maintained. Gone were the leakage problems. We even took a patent application on this. But the tender was Belgian and we did not even get a 'thank you' after. Nevertheless the impulses from aeronautics helped us to develop a new concept, better than the one currently under construction.
This experience made us realize that the solution might be hidden in this previous experience with GRP. After a brainstorm session of the engineering department of Octatube the following idea was conceived: the roofs would be made as giant surfboards of foam with GRP skin, creating 5 different GRP sandwich roof wings with a maximum length of 30m and a maximum width of 15 to 20m. For the tender we decided to work out two concepts, one with a tubular steel structure as described in the tender with a GRP covering and our entire GRP stressed skin sandwich roofs, the latter being one million euro more expensive. Two days after the closing date of the tender we were called by Avi Halberstadt, the local representative architect of Moshe Safdie, stating he saw our proposals and referred to it as 'an amazing solution'. A sign that they did not think of this concept themselves, which might be the biggest compliment. When we had to explain the consequences of the GRP sandwich in Israel the amazement only grew. The big wings would have to be constructed in one of the empty ship building halls in the Netherlands, as the wings would have to be turned upside down after construction of the top stressed skin layer in order to apply the lower layer. This meant a hall with minimal working width of 25m and a free height under the crane of 20m at least. After completion of the GRP top skin, the object had to be rolled over, turned and the bottom skin had to be applied. After completion they would be loaded on an open inland vessel and towed to the port of Rotterdam, where a specially chartered ship in which the 5 wings could be stacked vertically. After going for anchor on the coast of Tel Aviv a giant freight helicopter would lift the roof wings one for one from the vessel on a route to the shore, 5 km inland during the night, to position the roof wings on the flat open building site. A mobile crane would then swing the roofs on top of the columns. The rest of the construction process would be rather conventional for Octatube. The whole shipment and air transport was pretty special and expensive. After I explained the logistics of this alternative proposal. My representative Boaz Brown heard the architect Moshe Safdie mention to the chairman of the building team: *"you should try to get the one million extra"* in Hebrew, of words of that meaning: at least a sign that he was very impressed.
After a fiery discussion of the building commission the outcome was that the steel structure option was about on the average tender price while the GRP was still considered quite expensive, but undoable the most appealing concept. Moshe Safdie, with whom we had worked before on the Samson Center in Jerusalem, stated the idea was unbelievable and never done before to his knowledge. The response of the chairman of the building commission was to invent other logistics in order to reduce the price.

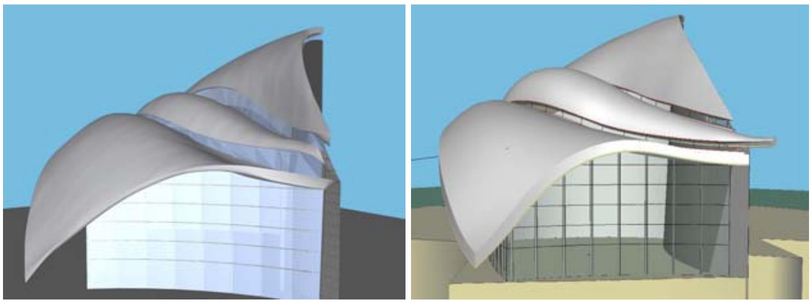

Figure 1-2. The Rhino model of Moshe Safdie & Associates and the first redesign in Maya by Octatube.

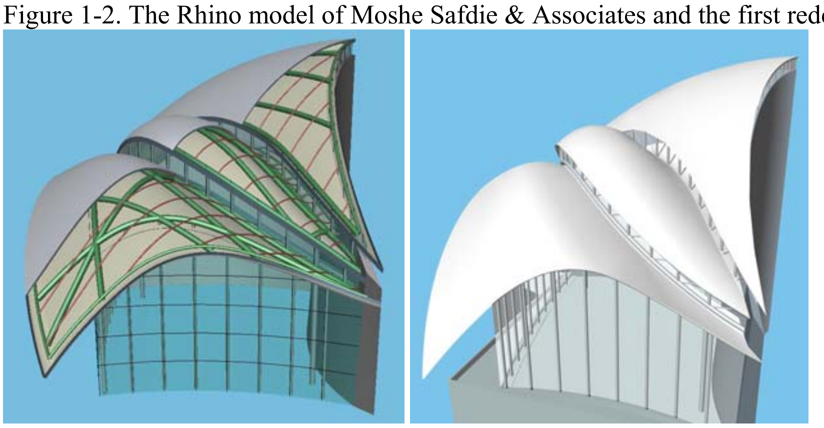

Figure 3-4. Two alternative constructions: a steel structure of CHS circular sections (left) and the structural sandwich structure (right).

2. REDESIGN & PRE-ENGINEERING CONTRACT

In the course of the design development we could redesign the rough contours given to us in the tendering stage by Safdie as a scan from a 3D material model imported in Rhino. For the engineering this basis was not usable to work with. By analysing different cross sections from the model and connecting these in fluent lines a usable model was developed. We redesigned the ensemble in Maya (3D CAD software). This program appeared to be an excellent medium fort designing the different components. Also in the same program the constituent parts could be defined and combined into the total composition: sandwich roof wings, columns and glass façade panels. The design included the reinforced concrete walls, the support plates of the concrete tops for the anchoring of the columns, the short and long columns, the facades and the roof wings and the intermediate glass sleeves.

At the same time the global analysis was made of the structural behaviour of the GRP wings and the steelwork. In this time we worked on two alternative constructions: A steel structure of systemized CHS circular sections, covered with a thin GRP sandwich as the roof covering and a separate ceiling material and the 'golden' alternative of the structural sandwich structure.

The negotiations with the client had resulted in changing of the subcontractor for the polyester work. Polyproducts bv remained at a too high level of costs to successfully hope for a reasonable contract and they were replaced by Holland Composite Industries bv of Lelystad, NL. They had previously made hulls of motor yachts and sailing yachts in GRP up to 30m length in vacuum-injection method, which was an excellent starting point for the development of the structural sandwich panels. They employed a Dutch engineering firm Solico of Oosterhout NL, who started to analyse the GRP alternative globally. The two structural analysis were compared and matched.

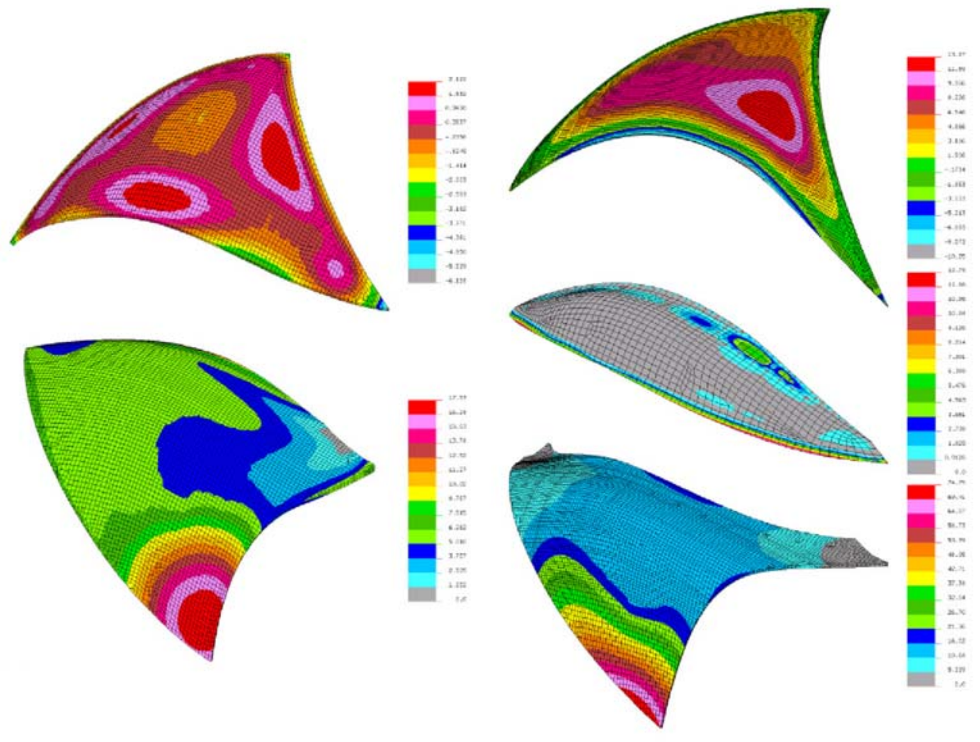

Figure 5. Structural analysis of deformation of the GRP sandwich roofs made by Solico. Left, the upper and lower wing of 'The Library'. Right, the upper wing, the central body and the lower wing of 'The Great Hall'.

At the same time a prototypes were made of both alternatives: steel structure with local foam covering and the integral sandwich. Both prototypes were shown to architect Moshe Safdie, together with the first results of the computer work in July 2003. The pre-engineering had indeed resulted into a dramatic reduction of the cost price as we were more and more familiar with the experimental sides and its solutions. The original quotation was reduced to around the original average price level, thanks to the results of the pre-engineering contract. This pre-engineering contract was a wise decision, which we often advocate in The Netherlands, but hardly ever receive in experimental projects out of fear for monopolisation. But specialization leads to monopolies. Yet this is a respectable way of progressing through a revolutionary innovation. Who is going to invest to accomplish a great leap forward in technology against which reward?

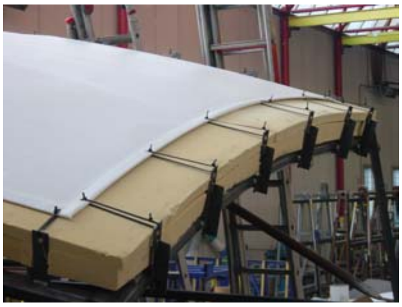 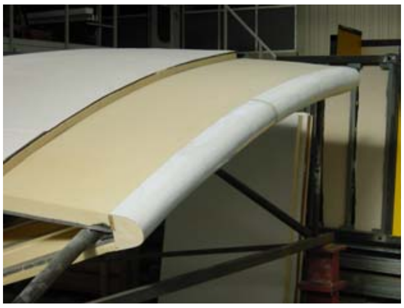 

Figure 6. First prototype with a stressed membrane.
Figure 7. Third prototype to be locally produced.
Figure 8. Fourth prototype, a prefab sandwich construction.

3. FINAL DESIGN

The route from redesign and pre-engineering to final design took one year involving 5 to 6 engineers. The architect visited Delft twice in that time to check the progress on the design and the new prototypes that were made on his specific instructions. We had agreed that, in contrast with previous projects there would only be one party involved with computer work, in this case Octatube and the architect could only supervise and give instructions behind the monitor. We had informed him earlier about the design considerations in a more than 30 clearly analysed and heavily illustrated letters. Moreover, the impulses from the development of the prototypes, the production methods involving moulds and injection production plus the future assembly of the structural seams and the structural behaviour of the total wings, all had a deep impact on the final design and had to be fixed by the responsible contractor, in this case Octatube. With these revolutionary developments: our 3 adages of “design and build in one hand”, ”the integration of architectonic, structural and industrial design” and “development of new products” are quite right. Respecting the wishes of the architect an intensive design and engineering route was followed, co-ordinating the two co-makers Holland Composites and Solico Engineering as indispensable. The urge for innovation, courage, spirit of enterprise and a certain naivety (not to know on forehand what hindrances will come in the future prepared the embedment of an engineering with multiple degrees of innovation. During the entire process the design methodology as development for special components, consisting of 3 mains phases: Design Concept, Prototype Development and Production, as published in [3] were followed quite literally.

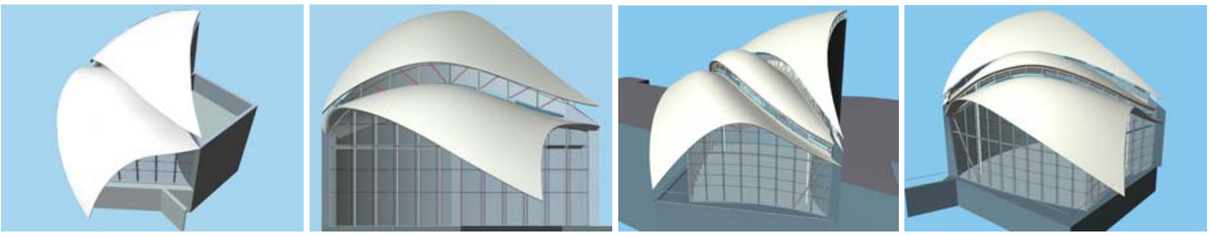

Figure 9-12. Birdseye and frontal views of ‘The Library’ and ‘The Great Hall’.

4. FINAL ENGINEERING AFTER FULL CONTRACT

The final contract was agreed on the basis of the adapted quotation and the approval of architect Safdie. The final engineering started on the basis of AutoCAD and Mechanical Desktop and the final analysis incorporating the final production methods of the GRP wings, testing of the connections of the sandwich panels on de-lamination, assembly connections loading deformations, fire resistance and logistics in the Netherlands, the transport in special open containers, assembly on special moulds on the building site, jointing and finishing and hoisting into position. After the design phase of one year the engineering inclusive testing also took one full year.
Due to political change in government from the labour party of Rabin to the Likhoud party of Shamir, all proposals were reviewed by the local government bodies with extreme attention, were many unforeseen and sometimes un necessary problems were detected and had to be neutralized. The counter wind took also the continuous attention of many of our engineers. Many people in Israel would like to see the project unfinished. Two professors of the TU Delft, faculty of Aeronautics, prof. Adriaan Beukers and prof.dr. Michel van Tooren were involved in a second opinion on the supplied engineering, directly commissioned by the client of the friends of the Rabin Center.

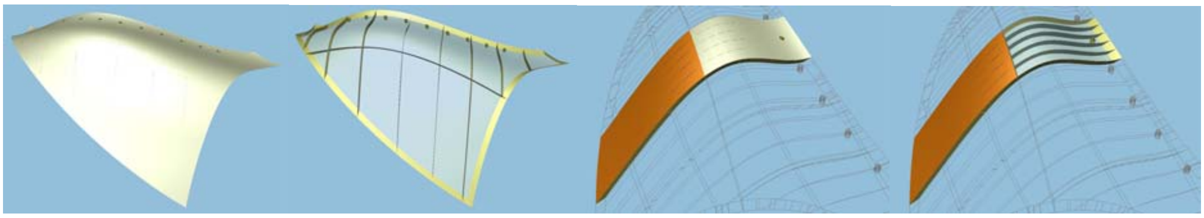

Figure 13. Lower Library roof, showing the segmentation and internal stringers

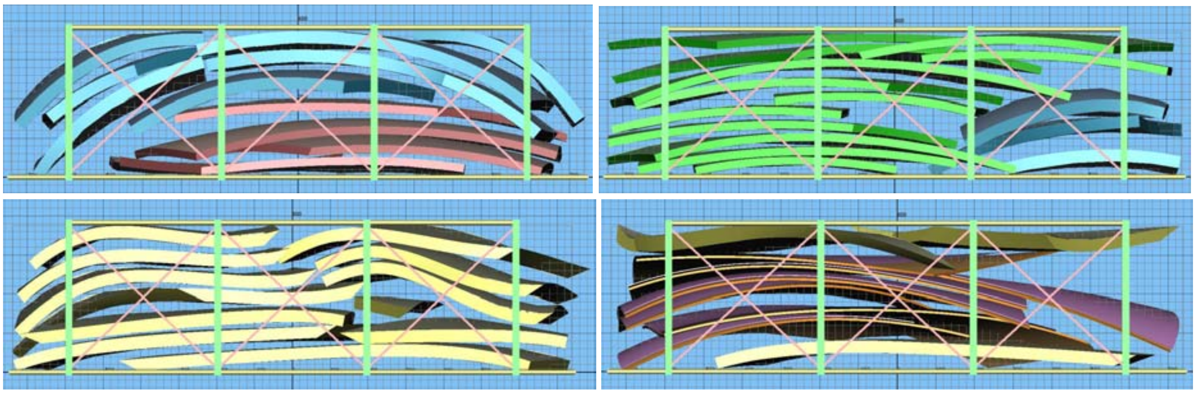

Figure 14-17. 3D drawings of the transportation of the roof segments in open containers

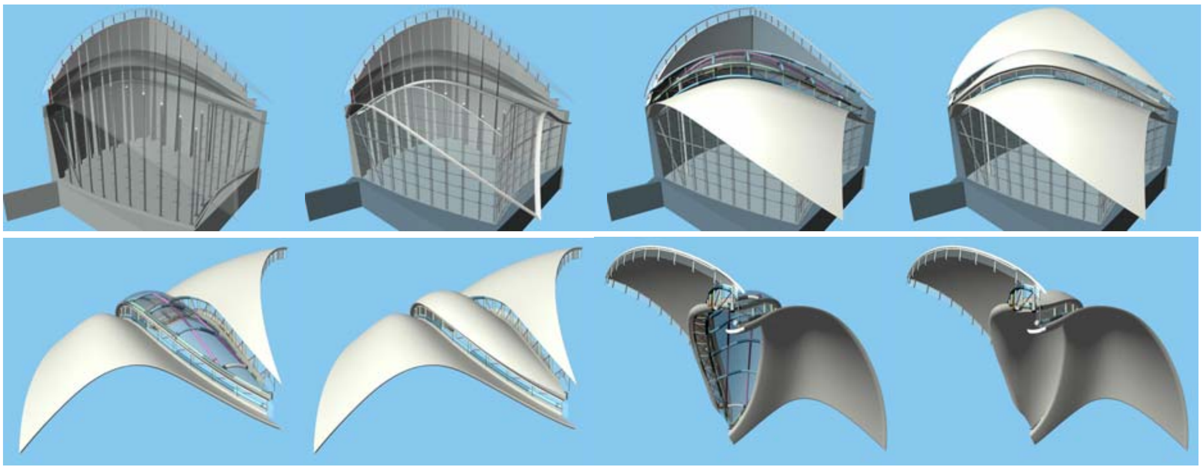

Figure 18-19. The Great Hall roof wings

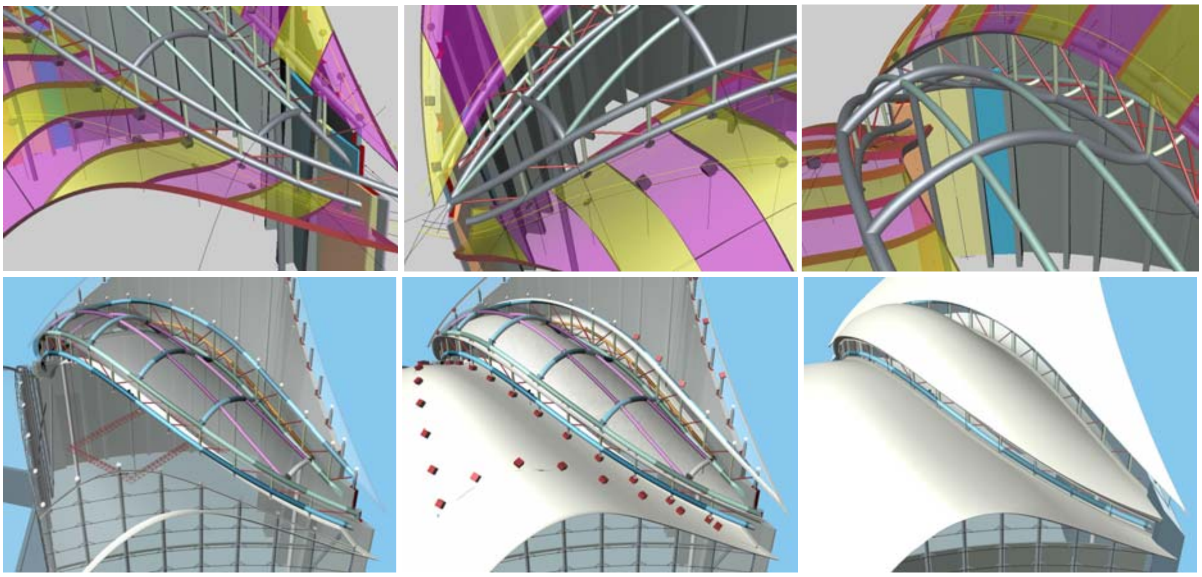

Figure 20-25. 3D Engineering drawings, showing the *central body*, GRP sandwich segments and *inserts*.

5. PRODUCTION AND INSTALLATION IN 2005

From January 2005 onwards the production went into operation and the third year of experimental production and assembly started with experimental production of the components on the negative moulds. We started with the smaller roof of the Library.

The production technique used in this case has been taken from standard production techniques of producing sailing ship hulls. Holland Composites had produced ships with hull lengths up to 30m. The competition of Polish and Slovenian producers forced them look for other markets. They produce the space boxes of which some 120 were built one year ago in Delft. Experimental vacuum injected productions meant a clever step.

The production is very engineering intensive. The foam blocks of polystyrene have been milled accurately by Marin to negative moulds from CAD/CAM files. When the milled moulds arrive at Holland Composites, the surface is covered with a foil. On top of this surface a thick layer of coating and the first glass fibre mats are applied. Using vacuum-injection, the glass fibre is impregnated with polyester resin. Since the resulting layer of GRP describes the desired form in the best possible way, this will become the upper layer of the roof. After this layer is hardened, fire-resistant polyurethane blocks are sawn and applied to the roof layer. Between these blocks long glass fibre strips are placed, these will become the *stringers*. This are the structural ribs in the sandwich as a replacement of the original steel structure. The foam blocks are subsequently covered with more glass fibre mats and a foil for the next vacuum-injection. The polyester is also injected between the blocks, making the glass fibre strips GRP *stringers*, thus creating a structural connection between the upper- & lower layer. The foam block make sure that a counter pressure is present if an unfavourable load was to occur on the roof. Local buckling of the GRP sandwich is prevented by this mean. After production of a roof, they are placed on a temporary structure in order to fit all the segments: the wing-shape becomes clearly visible now. Due tho the relatively large measurements of the segments, we had to create special open containers in order to ship them to Tel Aviv. In May 2005 the two wings of the ‘ Library’ are shipped to Israel and arrived on the building site. Here they will be assembled to be hoisted on the steel columns and truss.

In the mean time, in the production hall of Octatube , we are busy with the columns the roof rests on. Next to that, these columns also bear the load of the frameless glass façade. Making these columns is mainly a routine job for Octatube, the only difficulty being the connection between the columns and the roof. During the production at Holland composites steel *inserts* are placed within the sandwich. The location of these inserts is already determined and printed on the moulds at Marin. Specially developed ball-and socket-connections on top of the columns are bolted to the *inserts.* Therefore, deformation due to wind loads has no effects to the GRP sandwich. Next to that, the ball-and socket-connection provides in the possibility to cope with the tolerance of approximately 25mm between roof and column.

The largest challenge for Octatube proved to be the *central body*: the central part of the “Great Hall”. Due to the large forces from the upper and the lower roof wings amongst others, this part of the roof has to cope with, unfortunately steel was the only solution to make this span possible. This resulted in a complex structure of tubular steel, later to be fitted with thin GRP panels. According to the 3D computer data, various tubes were rolled in both 3D (two directions) and 2D (one direction). Because accurate 3D rolling is a rather complex procedure, the 2D rolled tubes possessed a greater accuracy. The 3D tubes, mainly situated in the length of the *central body,* at best approaching the desired shape, therefore had to be connected to the accurately shaped 2D tubes. Like the 3D shape of the *central body* alone is not complicated enough! Nonetheless, after a lot of thinking and welding an impressive “artwork” came into being. At Holland Composites the entire *central body* was assembled in order to fit the panels. After every panel is fitted, the structure is disassembled en transported to Tel Aviv. In Israel it will be assembled in two parts, hoisted on its position and only later these two parts are connected

Figure 26-27. The *central body* of the Great Hall

Figure 28-30. 3D drawing of the columns with the wing *connectors* and photo's of a 1:1 scale prototype

After the production of the roof parts of the lower wing of the Library, discrepancies between the theoretical drawings and the practical distortions and tolerances from shrinking of the polyester resin in the vacuum bags were measured. Tolerances because of warping of the negative moulds resulted in unforeseen deformations of the produced GRP components. These components together had to form the ruthless smooth surface of the complete wing in the end.
All aspects were approached in an engineering manner: measuring, analysing problems and deducting solutions. Improvisations bring the Law of Murphy nearer. Analytical engineering in the best traditions of the TU Delft made the initial amazing, improbable design solution finale a reality.
The resulting design is a combination of structural design, with architectural flavour, incorporating the technologies from aeronautics, ship building, industrial design and geodetic surveying and poses an example of multiple innovation of technology, thanks to the involvement of co-makers Octatube International bv, Holland Composites Industries bv and Solico Engineering.



Figure 31. Milling machine at Marin.
Figure 32. Milled negative-mould.
Figure 33. Vacuum injection of the top layer on foam block at Holland Composites.

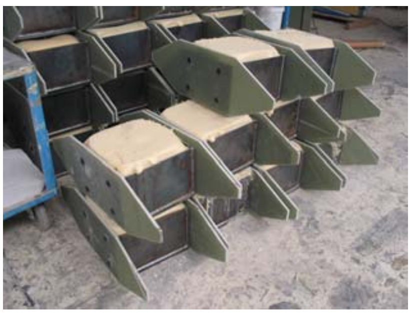
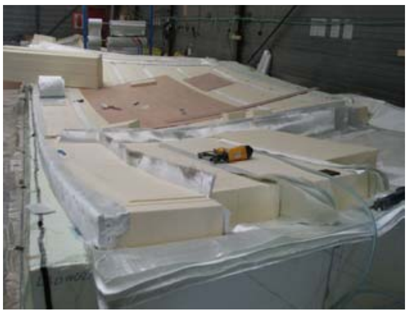
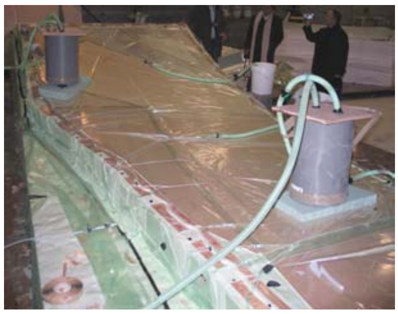

Figure 34. *Inserts* to be placed in the sandwich in order to make a connection between the roofs and the columns. The foam inside the *inserts* prevents polyester to gather and thus creating concentrated extra weight.
Figure 35. Placement of foam blocks and glass fibre strips between the blocks, which will become *stringers*.
Figure 36. Vacuum injection of the bottom layer.


Figure 37. Fitting of the roof segments (lower wing of ‘The Library’) at Holland Composites in March 2005.
Figure 38. Building site in Tel Aviv zoomed in on ‘The Library’ with the truss and columns already installed.

Figure 39. Open container at Holland Composites with the roof segments ready for shipment in April 2005.

6. CONCLUSION

The resulting design of this contribution shows that building technical design, like architectural design and urban design leads to an integrated process. In such processes many disciplines are collaborating and have to be coordinated throughout the entire process inclusive all of its unforeseen and experimental stages. The result of this process have to be integrated into one technical artefact that satisfies all requirements and gives efficient answers or compromises in all of its life phases, be it conceptual design, material design, detail design, engineering, productions, assembly, installation, loading behaviour, functional use as a building, meaning of the artefact as a building, (even as Architecture) and in its context / surroundings, in its meaning as part of the Monument for the Yitzhak Rabin Museum. At the faculty of Architecture designs usually are wide, integrating many aspects, hopefully all related aspects that designers can think of. Even later uses have to be foreseen in the form of flexibility in use for future functions. The discussion between designers from the ‘designing’ faculties of Architecture and Industrial design on the one hand and engineers from the ‘constructing’ faculties on the other hand stem from the integral versus the partial approach. Society expects from scientific designers that perfect solutions for society are developed. These solutions are not only the functional and technical solutions. They have to include use by people, social use and psychological consequences. It may be true that the well-known restrictions in the volume prices of the building industry, as posed by the clients in the building industry, lead to traditional and well known technologies, also the entrance thresholds in the building industry are low and competition is fierce. But sometimes experiments are driven through by persistent designers, willing to wander though the entire experimental development process, able to solve all foreseen and unforeseen problems.

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