Designing and Prototyping of a new Generation of Composite Sandwich Structures for Free Form Architecture

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Abstract

The design & build process of the liquid design roofs for the Rabin Center in Tel Aviv, that took place at Octatube's of Delft NL, in relation to the Blob Research Group, under leadership of prof. Eekhout at the TU Delft. Through an interdisciplinary approach and a dynamic parallel process of theory & practice, which in its turn mutually stimulate each other by new concepts for structural systems and Blob technology.

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

1. Introduction

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. It has been boosted again by the development of 'Liquid Design' / 'Free Form' architecture or 'Blob' architecture. 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 behaviour. This type of architecture is in a sense 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 m2 budgets of the building industry. This is the driving force of enlarging the traditional integration between architectural, structural and industrial design to incorporate also aeronautical design, yacht design and to develop 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.

2. Invitation to the project

In November 2002 the tender drawings of a design by architect Moshe Safdie from Boston USA as apart of the Yitzhak Rabin Center in Tel Aviv were received at Octatube's. The building design provided for two top building parts: the Great Hall and the Library. Both hall designs had remarkable and plastically designed roofs that resembled dove wings as a tribute to Rabin. Moshe Safdie is well known in world architecture since he designed the 'Habitat' of Montreal in the World Exhibition of 1967 as a then 27 year old architect [1].

The complicated liquid design roofs of the Rabin Center contained in the tender were analyzed by Ove Arup of New York to exist of a system of seemingly arbitrary open steel profiles with a layer of concrete on top. The specification left the construction of the roof cladding to the contractors. On top of this the architect requested a seamless solution in the roof.

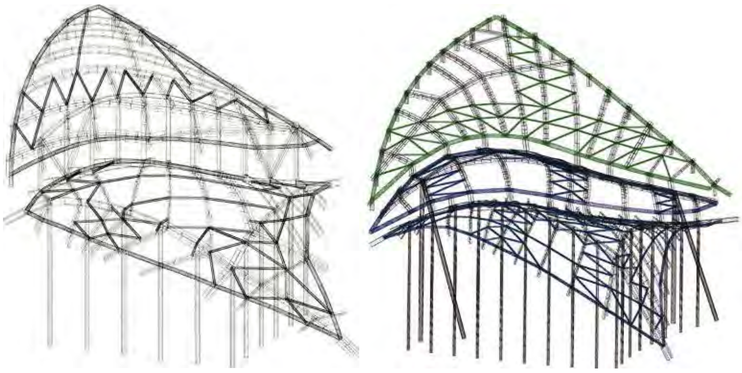

Fig. 1-2 Tender drawings made by Arup, New York. Left, 'The Library;' right, the Great Hall

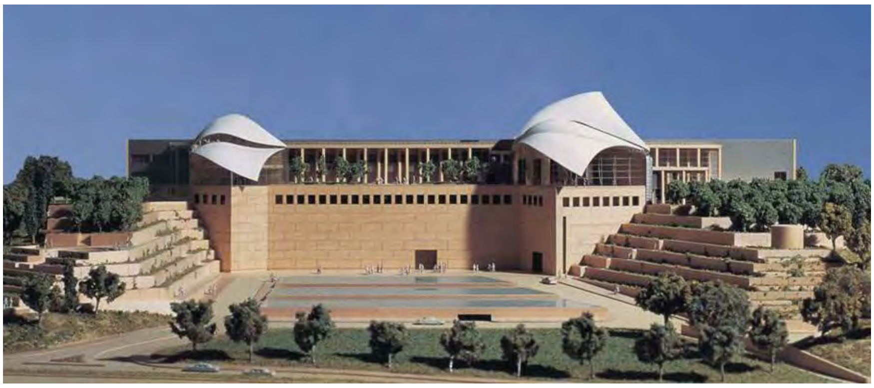

Fig. 3. Architectural model of the Rabin Center, Tel Aviv (courtesy: Moshe Safdie & Ass.)

2. Preparing for Tender

For two months the tender drawings and the thick specification were not given much notice. It seemed better to leave this project to one of the competitors. The requirement of a seamless surface would make any prefabricated system very difficult. The success would depend entirely from local labour and local supervision, which a prefabrication industry does not like. However, the client and his building manager kept on reminding of the tender date. They even postponed it even one month. It seemed difficult for them to find a trustworthy answer, so was their message. Finally the challenge to find a creative innovative solution for this problem was to bright for technical designers and inventors to let go.

A new system for the structure and the construction was conceived. One year before the Municipal Floriade pavilion of Asymptote Architects from New York had been designed and built by Octatube. It was a struggle with 3D-aluminum panels of 5mm thickness which were deformed via explosion deformation on negative concrete moulds, formed on positive polystyrene moulds. This process was done at the premises of Exploform in Delft, established on the TNO-research institute at Delft because of the government allowance of use of explosives.

Fig. 4-7. Video captions of an 'Exploform explosion' in a water basin (from: exploform.nl)

Fig. 8-10. Left over polystyrene moulds used to make negative concrete moulds (left), exploformed aluminium panel (center) and fitting of a panel on a wooden fitting mould (right).

3. The Principle of the Stressed Skin Sandwich

So in a few brainstorms the basic idea was to make the roofs as giant surfboards of foam with stressed upper land lowers GRP skins. The size of the roofs, subdivided into 5 different roof wings was max. 30x30m². Each wing had a max length of 30m and a width of 15 to 20m. It was the technology and the resulting technical product that fascinated. Polyproducts bv was invited to join the tender team of Octatube, as well as Haiko Dragstra. Three successive brainstorms were organized respectively on the product idea, the structural concept and the logistics & pricing. It was decided to work out and price the stressed sandwich skin alternative as well as the original tender specification of the steel structure with a non-described, free covering as the variation. The proposed cladding was a variation on the original tender design, derived from the mega-sandwich idea, but now in a thinner scale version of 50 to 80 mm thickness, as it had only to span the purlins between the steel structure elements (3m). This sandwich had to be finished with a GRP skin.

The budget calculations resulted in the alternative as 1 million Euro more expensive than the tender prescription: a steel structure and a thin 80 mm thick GRP sandwich cladding as the variation in stead of concrete. The high cost were due to the polyester parts. It was argued that that the maximum extra price would be 1 million Euro. But it was expected that any architect would fall in love with the alternative of self-supporting stressed skin sandwiches.

4. "Extremely innovative, but too expensive for us"

Only two days after the tender closing date a telephone call was received from the local Israel representative architect, speaking on behalf of Moshe Safdie: Avi Halberstadt. He gave the compliment that the architect saw the alternative proposal as *"an amazing solution".* The model showed that in the design the corner details had not been accurately designed yet and that the overall stability was unsatisfactorily. The design needed much engineering work still. The building commission went into a separate meeting. After one hour of fierce discussions, the outcome was: The tender original with the GRP covering was practically on the average tender price level, while the alternative proposal was indeed very attractive from viewpoint of its extremely innovative design and construction, but was only one million Euro too high in price. Knowing the intellectual value of the alternative proposal, it was a fair extra price for this yet unbuilt idea. Normally, however, technical alternatives are more efficient solutions for the contractors and are normally lower in price than the original. The response of the chairman of the building committee was to invent a logistic solution for the alternative proposal so that its price level would be on the average price level again. He gave an indication to maybe transmit the foam machining and the GRP production to Israel to save on shipment costs and on labour costs at the same time. So this was the message that had to be taken home on April 29th 2003. The committee wanted to speed up their decision, so an alternative idea had to be presented within one or two weeks.

5. Rethinking the alternative

Back in Delft the consequences with the in-house engineers and with the outside team of co-makers were discussed. If the alternative could be realized, it would be a world innovation. But realization was far away yet. If more project activities had to be done in Israel, Israeli partners had to be selected. This Israel alternative was to go in a number of steps. First the decomposition of the big wings into conventionally transportable components would be done, which could be assemble on site on a jig. The shells would be finished at the seams between the GRP layers. The surface would be given a final top layer or top coat on top of that. If this would not bring enough reduction in price, the second step would be setting up a consortium and having Complot machining the polystyrene blocks in Tel Aviv on the building site and have Polyproducts bv setting up an Israeli GRP plant on site where the most likely position would be the vertical position of the roofs. That would lead to assemble the roof as a wall from stacking the polystyrene blocks on top of each other, so that both skins could be treated simultaneously, the shrinking of the foam could be controlled much better and the roof wing, build like a wall, could be easily lifted from between the two 20m high scaffolding walls by a mobile crane. However, the machining of the polystyrene blocks in Israel seemed very expensive: this subcontractor was not experienced in estimating larger productions than mock-ups. The co-makers did not have enough experience with export to step into this idea. Making a tough export consortium based on ample experience, specialism and mutual trust takes quite some time and always one of the team members has to guarantee for the others continuity. And often, when the production can be done for the home market, why go abroad where people speak all kind of foreign languages. The Dutch have always been abroad. Why not follow them in this case? But, alas, the price reduction was not reached. A dramatic step had to be taken. Just to be sure the second alternative, which was an answer to the original tender, was formed with a steel space frame and a locally made sandwich panel system on top, forgetting the world novelty of the stressed skin sandwich, just to stay in the race. But at the same time work was continued on the prime sandwich alternative.

6. Redesign & Pre-engineering Contract

In the course of the design development the redesign could be made on the rough contours given in the tendering stage by Safdie as a Rhino scan from a 3D material model. 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. The ensemble was redesigned 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 two alternative constructions were worked on: A steel structure of systemised CHS circular sections, covered with a thin GRP sandwich as the roof covering and a separate ceiling material and the innovative alternative of the structural sandwich structure.

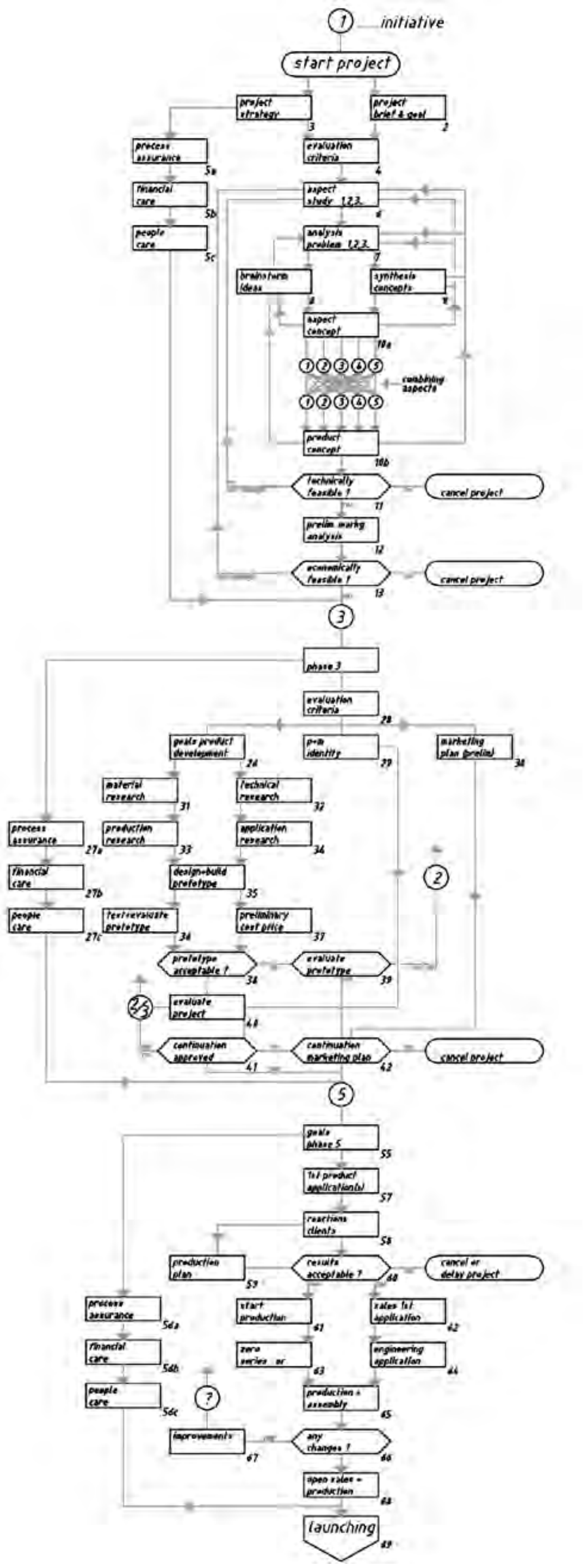

Fig. 11. Organogram for Product Development (phase 1,3 & 5) [2].

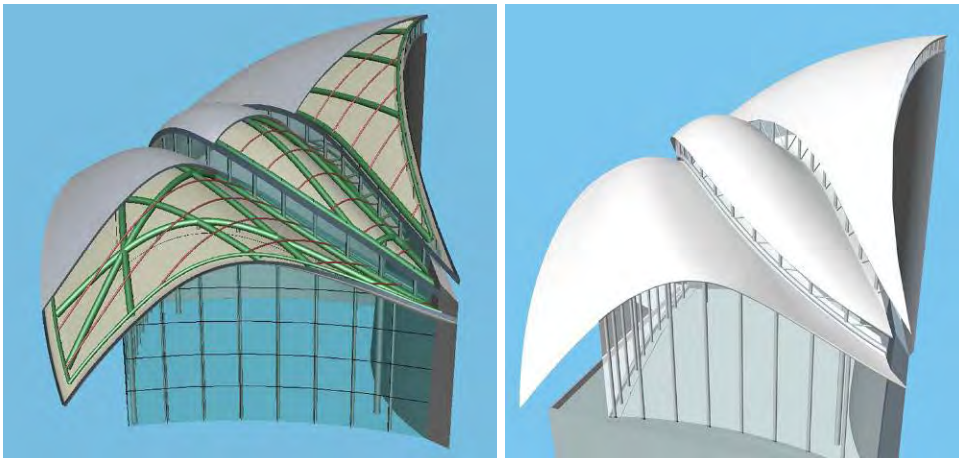

Fig. 12-13. Two alternative constructions: a steel structure of CHS circular sections (left) and the structural sandwich structure (right).

The negotiations with the client had resulted in changing of the subcontractor for the polyester work. Polyproducts bv was 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 proposed vacuum injected segments that later could be joined of maximum 3.5 x 15 m. 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. At the same time prototypes were made of both alternatives: steel structure with local foam covering and the integral sandwich construction. Both prototypes were shown to architect Moshe Safdie, together with the first results of the computer work in July 2003.

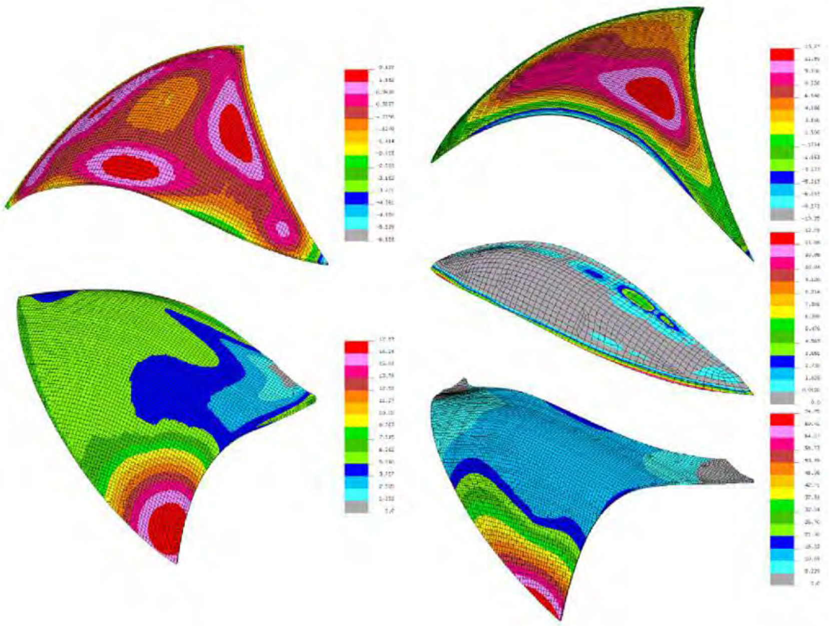

Fig. 14. Structural analysis of deformation of the GRP sandwich roofs made by Solico. Left, the upper and lower wing of 'The Library'. Right, the upper wing, the central body and the lower wing of 'The Great Hall'.

The pre-engineering had indeed resulted into a dramatic reduction of the cost price as the experimental sides and its solutions became more apparent. The confidence of the producers was grown enough to give the guarantees required as if the building method had already been used before. Largely due to the separate pre-engineering contract granted by the client before the main order of design & build, the experimental prototype contract.

7. 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. 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 behavior 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: Octatube's three 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, coordinating the two co-makers Holland Composites and Solico Engineering as indispensable. 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 [2] were followed quite literally, see figure 11.

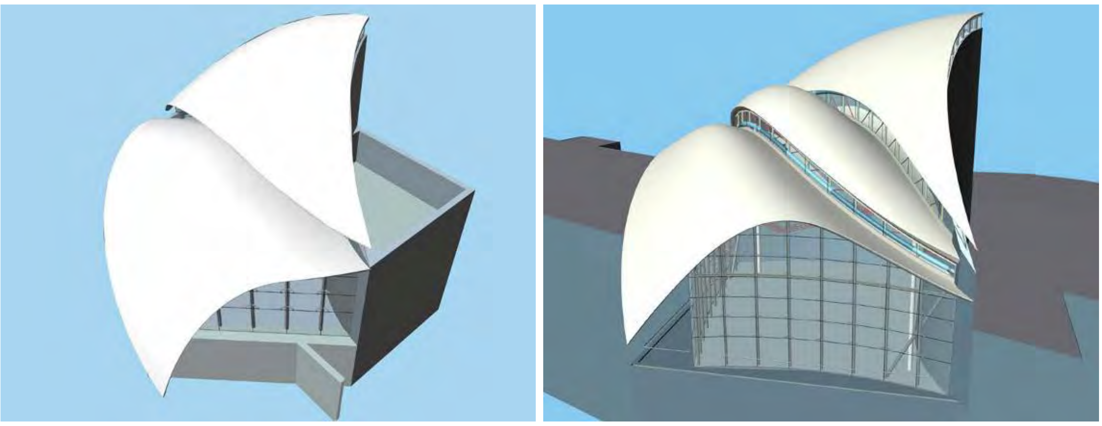

Fig. 15-16. Post engineering bird's eye view of 'The Library' and 'The Great Hall'.

8. Final Engineering after Full Contract

The final engineering started on the basis of AutoCAD and Mechanical Desk Top 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 experimental design phase of one year the full contract was only stated and the engineering inclusive testing also took one full year.

9. 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. The smaller roof of the Library first to be produced. Tolerances because of warping of the negative moulds resulted in unforeseen deformations

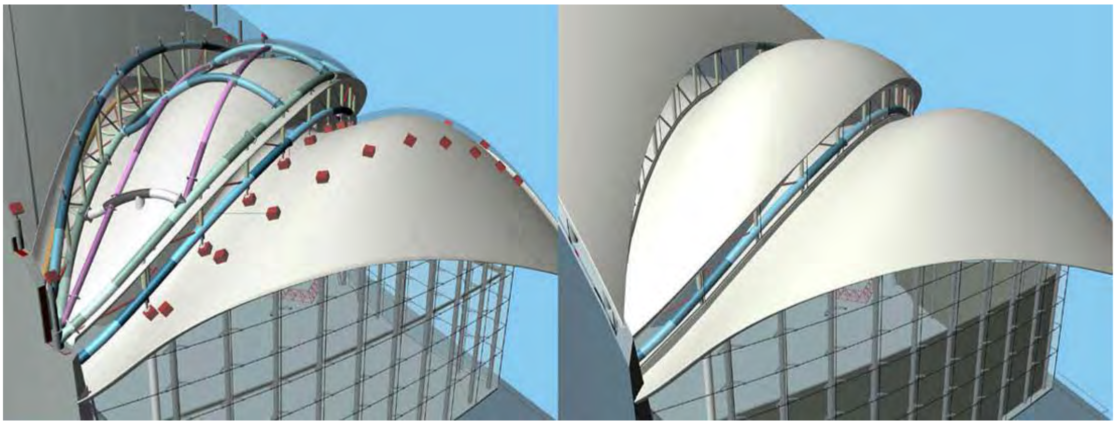

Fig. 17-18. Close-up of 'The Great Hall' wings with insert points for connectors to connect the wings to the columns and structure of the 'central body'.

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.

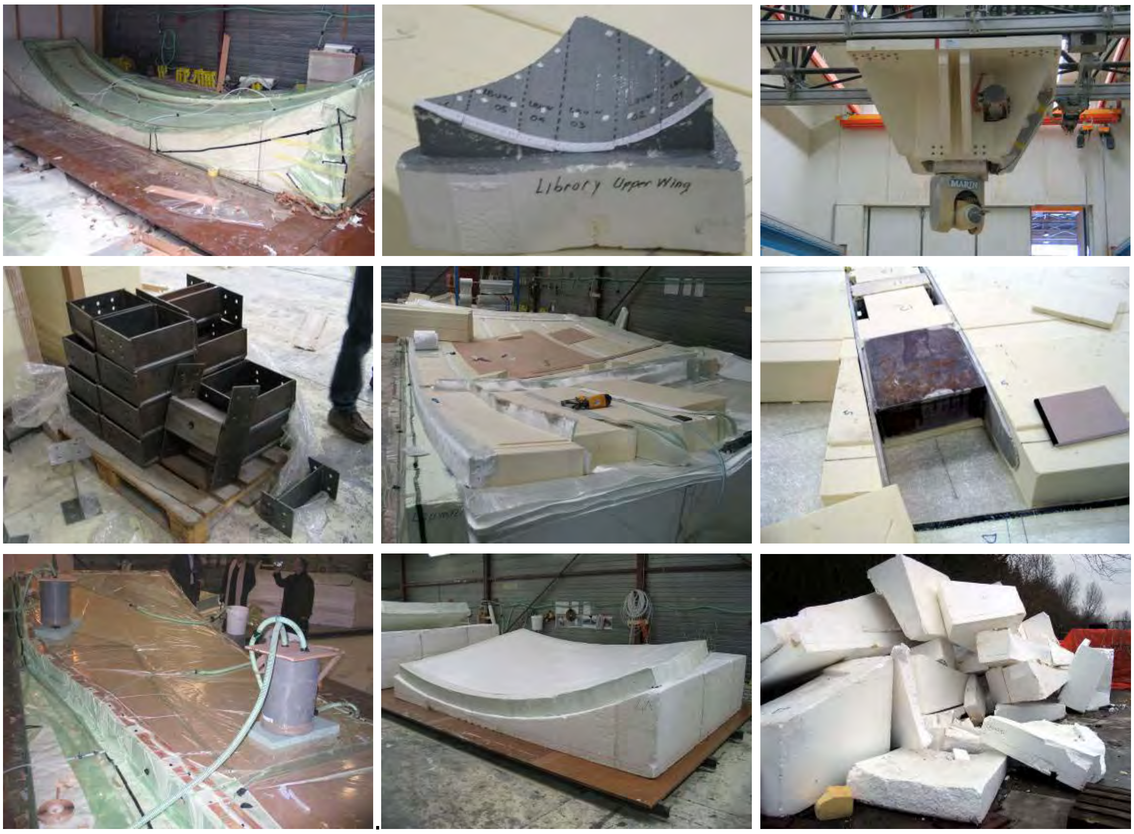

Fig. 19-27. Milling machine at Marin (19), scale model of upper wing of 'The Library' (20) and production of the roof segements at Holland Composites (22-28). Vacuum injection of the top layer on foam block milled by Marin (21). Insert to be placed in the GRP sandwich roofs in order to make a connection between the roofs and the columns (24). Placement of foam blocks and glass fibre matts, which will become stringers (23). Vacuum injection of the bottom layer (25). Final result, in this case an early prototype (26). Discarded foam moulds (27).

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. It poses an example of multiple innovation of technology, thanks to the involvement of co-makers Octatube International bv, Octatube Engineering bv, Holland Composites Industries bv and Solico Engineering. The production is very engineering intensive. The foam blocks of polystyrene have been milled accurately to negative moulds from CAD/CAM files. The upper surfaces were epoxy toughened. The vacuum bag package of top layer weaves, insulation layers inclusive the inserts and the stringers and bottom layer weaves are injected with polyester resin and cured within 4 to 8 hours. The curing causes individual deformation that only appear in assembly by the non-continuousness of the upper surface of the roof wing after assembly from parts.

Fig. 28-29. Roof segment (left) and fitting of all the roof segments of the lower wing of 'The Library' at Holland Composites in March 2005.

Fig. 30-31. Building site in Tel Aviv zoomed in on 'The Library' with the truss and columns already installed (left). Open container at Holland Composites with the roof segments ready for shipment in April 2005.

10. Conclusion

The resulting design of this contribution shows that building technical design, like architectural design and urban design leads to an integrated process. 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 are usually wide, integrating many aspects, hopefully all related aspects that designers can think of.

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. The Blob Research Group of the TU Delft (under supervision of Mick Eekhout) has done research in this area. The Octatube company acts as an experimenting design & build company / prototype laboratory for the TU Delft: it is a product of as Delft Scientific Design.

Fig. 32. Rabin Center after completition.

Fig. 33. Interior view of the Rabin Center.

References

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