

LORD OF THE WINGS

Research in Architectural Engineering Series

ISSN 1873-6033 [print]

ISSN 1879-8225 [online]

Volume 12

Previously published in this series:

Volume 11. A. Vogler, The House as a Product

Volume 10. U. Knaack and T. Klein [Eds.], The Future Envelope 3 – Facades – The Making Of

Volume 9. U. Knaack and T. Klein [Eds.], The Future Envelope 2 – Architecture-Climate-Skin

Volume 8. U. Knaack and T. Klein [Eds.], The Future Envelope 1 – A Multidisciplinary Approach

Volume 7. M. Eekhout, F. Verheijen and R. Visser [Eds.], Cardboard in Architecture

Volume 6. M. Veltkamp, Free Form Structural Design – Schemes, Systems & Prototypes of Structures for Irregular Shaped Buildings

Volume 5. L. Bragança, C. Wetzel, V. Buhagiar and L.G.W. Verhoef [Eds.], COST C16 Improving the Quality of Existing Urban Building Envelopes – Facades and Roof

Volume 4. R. di Giulio, Z. Bozinovski and L.G.W. Verhoef [Eds.], COST C16 Improving the Quality of Existing Urban Building Envelopes – Structures

Volume 3. E. Melgaard, G. Hadjimichael, M. Almeida and L.G.W. Verhoef [Eds.], COST C16 Improving the Quality of Existing Urban Building Envelopes – Needs

Volume 2. M.T. Andeweg, S. Brunoro and L.G.W. Verhoef [Eds.], COST C16 Improving the Quality of Existing Urban Building Envelopes – State of the Art

Volume 1. M. Crisinel, M. Eekhout, M. Haldimann and R. Visser [Eds.], EU COST C13 Glass and Interactive Building Envelopes – Final Report

LORD OF THE WINGS

THE MAKING OF FREE FORM ARCHITECTURE

Mick Eekhout

Professor of Product Development 1991-2015, TU Delft

General director Octatube Delft, NL

Sieb Wichers

Master of Science in Architecture & Building Technology

Project leader Rabin Roofs 2004-2006, Octatube Delft

LORD OF THE WINGS

© 2015 Mick Eekhout, Sieb Wichers and IOS Press

AUTHOR Mick Eekhout and Sieb Wichers

LAYOUT Manuela Schilberg, Saphira Jon, Octatube, Delft

MASTER DESIGN Sirene Ontwerpers, Rotterdam

This book is published online with Open Access by IOS Press and distributed under the terms of the Creative Commons Attribution Non-Commercial License.

All rights reserved. No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, without prior written permission from the publisher.

ISBN (print) 978-1-61499-549-4

ISBN (online) 978-1-61499-550-0

DOI 10.3233/978-1-61499-550-0-i

PUBLISHER AND DISTRIBUTOR

IOS Press BV

Nieuwe Hemweg 6B

1013 BG Amsterdam

The Netherlands

fax: +31-20-687-0019

e-mail: order@iospress.nl

PRINTED IN THE NETHERLANDS

PREFACE



Moshe Safdie [© Stephen Kelly]

Architects do not conceive nor realize buildings in a vacuum. They are part of a larger team of builders, craftsman, engineers and other experts who join forces and bring together diverse fields of knowledge. In the old days, architects conceived buildings within an accepted and limited system of construction, mastered by craftsman. So seamless was the process of conception and realization, so integrated in the familiarity of masonry and timber construction that much was left by the architect to the master builder to interpret.

The modern era brought about a fundamental change in the conception and realization of buildings. No longer could one rely on an accepted vernacular of construction familiar to all; the choice of methods, materials and systems abound. The knowledge of putting together these building systems is specialized. We are, today, familiar with the teams of engineers and craftsman that might realize a curtain wall, a space frame structure, concrete prefabrication, metal-forming assemblages and others. In each case a highly specialized team is essential to the projects' realization.

Alas, as a result of this new situation, we have all too often seen a disconnect between architectural conception and realization. The architects, on one hand, are often bound by procurement procedures, having to design to the last detail, and place their designs for competitive bid in which the product has been fixed without the input of industry. All too often complex architectural conceptions are conceived without such collaboration, and are realized in a manner in which this interdependency of concept and its material realization are at odds, all to the loss and to the detriment of the final result.

I've always believed that the fundamental principle of great architecture is that it must be inherently buildable. That is to say, it is conceived as the optimal realization of the buildings' systems in which it is to be realized, so that form, function and economy resonate with

the capabilities and character of the particular building technology. Towards that end we try to break away from the traditional: conceive-design-bid, and have realized by others' methodology in the building industry.

This book is the story of this collaboration. How the Octatube group, with its team in Delft, conceived and recruited individuals and fabricators from the field of fiberglass production heretofore applied to ship building, novel engineering and cutting-edge technology that enabled the realization of the dramatic structure now standing in Tel Aviv.

As is always the case, team collaboration boils down to teamwork between individuals. I particularly enjoyed working together with Mick Eekhout, who both in his capacity as President of Octatube and Professor in Delft University, conceived of the construction method, and thereafter, spent untold hours together with his staff and myself, personally, in evolving the design to its final form. Mick was supported in this effort by Sieb Wichers, a geometrist who translated our fluid free-forms into buildable components. Sieb went on to join our firm and facilitate the extension of these ideas to the Marina Bay Sands complex in Singapore, and the Art Science Museum within that complex.

I would like to salute both the spirit of collaboration and the fact that the project, in its realization, has demonstrated the importance and potential of architects, engineers and industry working together towards pushing the construction industry towards greater and greater achievements.

Moshe Safdie
Boston

CONTENTS

INTRODUCTION ix

SUMMARY xiii

01 STARTING POINTS AND TENDER 1

02 THE TENDER PROPOSAL 11

03 PRE-ENGINEERING AND PROTOTYPING 21

04 FINAL ENGINEERING 39

05 PRODUCTION 63

06 TRANSPORTATIONS 77

07 SITE ASSEMBLY & INSTALLATION 81

08 THE SLIP-STREAM OF COMPOSITE AND CARBON FIBRE FREE FORM SHELLS 105

09 CONCLUSIONS 115

10 EPILOGUE 119

11 REFERENCES 121

12 BIOGRAPHY 123

INTRODUCTION

'Liquid Design', 'Free Form' or 'Blob' Architecture are all expressive terms used to describe the beautiful art of seemingly freely formed geometries, non-definable by any regular mathematical formula and which are mainly driven by increasing capacity of contemporary computers combined with the desire of designers and engineers to give unique identities to their creations.

Following decades characterized by the development of membrane structures, systemized metal space structures, sophisticated tensegrity structures, glass envelope constructions and load bearing glass structures – free form architecture is now setting the trend in façade and roof structure design.

In a sense, the evolution of free form architecture is a direct consequence of architects and engineers being driven by the urge to explore new opportunities that the latest generation 3D design computer programs provide them with. Progression in 3D programs is now allowing designers to design geometrically complicated virtual 3D buildings, which are always 'one-offs' in shape and usually composed of non-repetitive components.

The resulting photo-realistic rendered buildings can be geometrically incredibly impressive and look stunningly unique. Dutch free form architect Kas Oosterhuis modestly refers to his designs - 'non-standard' architecture. Yet, the route to constructing these designs and producing their components in reality is paved with technical challenges, difficulties and experiments.

There is no wonder why while the possibilities and creative freedom offered by the new 3D technologies may be a dream come true for designers, the producing side of building industry often talks about 'free-form nightmares'. Free form designs are proved to be harder for fabricators and suppliers to deal with and the reasons are numerous, where budget demands is being the most pre-eminent:

On one hand, there are the demands for low budget from the client side; on the other hand there are the demands for costume-made, intricate components from the designer's side. The tension between budgets demands, supplying demands and tender demands forces fabricators and suppliers to come up with innovative technological solutions for product development, in a very short time.

Another primary challenge is the fact that standard timetables are applied to these absolutely non standard projects. While in more standard projects, timetables are already tight but somewhat achievable, realization of innovative free form projects needs more time than usual. Yet, in many of such projects, the need for longer research and prototyping time is not addressed and Design & Build contractors are expected to deliver their solutions in 'normal' times. This also limits the level of innovation in the building industry and consequently hurts the design. In the Yitzhak Rabin Center project, the need for special prototyping time and budget, as suggested by the contractor, Octatube, were addressed and understood by the architect, Moshe Safdie. But in most projects this is not always the case.

Also, applying typical m² budgets to these non-typical projects, which demand non-typical solutions, create another major challenge for Design & Build contractors to deal with. One way of which contractors are dealing with client's low budget demands versus experimental needs is to try and lower the costs of experiments by leaving traditional building processes behind.

For example, for the Yitzhak Rabin Center project, the contractor, Octatube, was required to use non-traditional CAD/CAE, CAM/CAB procedures and special production and surveying technologies; Consequently producing one-off GRP stressed skin sandwich components to allow for larger spans in arbitrary forms to become true freely formed 3D-roofs.

Integration of engineering and production methods is not the only solution for the challenges offered by free form designs. Integration with other disciplines and collaborating industries is imperative for the development of new free form designs. Consulting with professions from outside the building industry, such as: aeronautic designers, yacht designers and industrial designers becomes essential.

One of the most positive outcomes from these practices of knowledge exchange is that they actually starting to turn the building industry from a historically slow paced one, to a front-runner in cost effective solutions.

Designing and developing innovative structural systems for practical use in architecture is Mick Eekhout's greatest passion and specialty. As the founder and General Director of Octatube, Mick Eekhout has been leading Octatube to be a world renowned force in the building industry. Octatube is well-known for its ability to Design & Build complex, inventive, cost effective systems; providing the necessary research and development processes up until projects realization.

As an architect, structural designer and a pioneer of space structures, Mick Eekhout's designs for Octatube are characterized by a dynamic approach, which is incrementally evolving to adapt to new and changing architectural demands using its ever increasing in know-how and insight. Necessary adaptations are made according to but not limited to: scale of projects, projects demands and unique specifics, identity of the architect, the real time planning schedules, desired degree of experimentation and more.

Octatube started implementing its dynamic approach on smaller projects in the Netherlands followed by increasingly bigger projects [in scale as well as complexity] worldwide. All of Octatube's systems are designed and engineered at the main office in Delft, the Netherlands, together with the project's architect. Mick Eekhout always believed that his position as a professor at Delft University of Technology provided him with excellent opportunities for contemplation and sharpening the mind with colleagues from different disciplines and other faculties. He also believes that designing is tunneling results of scientific research to society and that the relationship between research and design are mutually indispensable. The ability to discuss the merits of design, development and research and to deliberate the valorization side of designing resulted in some of the building systems [see scientific site: www.mickeekhout.nl] being boosted and accelerated by know-how from other professions, faculties and industries.

One of the most recurring problems in component design and product development for architectural projects is the low threshold around the building industry. This easily leads to new, inexperienced competitors, with competition being based, sometimes, solely on low price offers. General contractors are used to [and in some countries obligated to] appointing subcontractors for pricing reasons only. This results in a lack of interest in entrepreneurial experimentations and an overall tendency for copying the results of the experimentation by others. The lazy policy of wait-and-see or the 'me-too' effect minimizes the experimental expenditure in the building industry and the experimental spirit along with it.

Experimental designers like Mick Eekhout, feel that this policy also stands in contrast to their vision, attitude and the freedoms that system designs require in order to evolve. Furthermore, when a new product is designed and successfully implemented in prominent parts of buildings, they usually become fully exposed in professional and scientific publications. Subsequently, this allows competitors to copy the applications and use them in their tender bids for future projects. Every new inventor in the building industry is haunted by this flow of events, whereby the ingenuity of a new system is fully exposed in digital/printed media to competitors. The negative impacts of exposing inventions and designs to the public domain without having them protected in some fashion is what led to the worldwide legislation of patent, copyright and trademark laws already in the 19th century. However, given the many different systems at hand and even more differentiated applications, intellectual property laws do not protect inventive development work. As a result, architectural and structural designers are left to look for new horizons; either new markets for existing products or new products for existing markets.

Luckily, copying other's innovations is not a fail-safe practice and 'copycat competitors' will find themselves miserably embarrassed for trying to use them without sufficient knowledge and experience. For example, a couple of copycat competitors that were tendering for the HaShalom [peace] project in Tel Aviv, made a mess of their copied systems and had to abandon the contract after reaward. Furthermore, the client regretted his decision to grant the contract to an Italian consortium; after seeing the engineering results he changed his mind, withdrew the contract and contracted Octatube. Octatube, which was the original designer company, redesigned, engineered, produced and installed the project in what one would consider as a miraculously short time, just to stay in line with the planning of the building.

The composite wings for the Yitzhak Rabin Center in Tel Aviv are the result of a well-defined experimental component design and development. In this one-off experiment, the geographic distance between the component design and production site in the Netherlands and the installation site in Israel imposed a hefty financial risk for Octatube. Therefore, the impact of design considerations on production, transport and installation had to be constantly monitored and adjusted when necessary.

Fortunately, the completion of the Yitzhak Rabin Center was very successful. This world novelty of engineering and producing technique of roofs for liquid designs had been published extensively over the years. The success of this experimental project triggered a handful of composite manufacturers to start designing and building composite facades in the Netherlands – what will hopefully lead to the establishment of a Dutch consortium of small and medium-sized composites enterprises [SME] dedicated to the building industry.

Furthermore, it seems inevitable that after duplication, multiplication and systematization of the developed composite technologies for architecture, the laws of economics will govern and the enterprising structural engineers and designers will have to develop new products and systems challenging the boundaries of contemporary cutting edge of technologies.

SUMMARY

Contemporary 'liquid design' architecture is characterized by their completely free form geometries, marking a new era in the construction industry: the renaissance of the shell structures; an innovative architectural stream which gained popularity already back in the 1960's and earned recognition with works of architects such as Felix Candela, but disappeared since.

The building industry calls these projects 'liquid design nightmares' for a reason. Realizing free form design dreams requires the highest skills available and often the transfer and adaptation of technologies used by other industries to the (generally slow paced) building industry. A great example of this is the experimental Yitzhak Rabin Center project, where a complete new construction type has been developed for the wing shaped roofs, which is described later on in this book.

This book portrays the experimental Design & Build process of the free form glass fiber reinforced polyester sandwich shells of the Yitzhak Rabin Center in Tel Aviv. A highly innovative adventure; the design and build included as much as 9 innovations in one process. Stacked on top of each other in this dangerously experimental project, these were:

- Free form geometry of the building;
- Use of glass fiber reinforced polyester as building material;
- Juggling with a lack of data transfer between computer programs;
- Vacuum injection production method for composite segments;
- New structural system of sandwich type shell structures;
- Complex interlocking of prefabricated components;
- Main production off shored to a composite yachting industry;
- Complicated site activities out of view at 5000 km from Delft;
- Building in a critical governmental approval environment.

In hindsight, perhaps too many novelties were introduced in this one project; however, despite the project's relatively small size, the message of its technically innovative development is worthwhile to be generalized for component design and product development in architecture. The book deals extensively and openly with the design, development and research aspects, as well as the engineering, production and realization processes of an entirely new generation of free form sandwich shell structures for architecture. You will also read about the uncertainties, the choices made and the lessons learned.

The principle idea of creating free form sandwich shell structures for this project, was influenced by the industrial glass fiber reinforced polyester (GRP) production processes used in the yachting industry. The idea was a result of Octatube's in-house brainstorm sessions as well as discussions with co-makers, their experienced advisors and professors of TU Delft. Using state-of-the-art design and engineering computer programs, the process of design and engineering on transfer and adaptation of technology from the yachting industry, relied heavily on the abilities and imagination of the technical designer to develop this complex process diligently. A Building Information Model (BIM) was introduced in this project purely out of geometric necessity; one cannot design and engineer the different components independently to fit into the total building as the technical composed artifact. Therefore, in order for all components to fit, all elements in this project had to be accurately described in 3D models.

The free form geometries of the Rabin Center's roof and the facades of the Library and Great Hall are composed of a combination of standardized, adaptable and free form components and elements; each with their respective geometry and restrictions. A great deal of attention was given to the tolerances between the different components and between their individual parts. While Minus-Tolerances components generally fit together quite well, with Plus-Tolerances the fitting process tends to be much more challenging and may require major in-situ adjustments that do not meet the architectural expectations. Generally, understanding of tolerance requirements during the design and engineering phase is very important; in order to later on juggle with the provided tolerances during the actual production and site installation phases. Tolerance requirements of the various production phases in this project, were influenced by a combination of technologies used in the construction and yachting industries. Also, architectural applications of these technologies demanded special developments and adaptations of for example the size of the roof wings, their transport, shipment and assembly. These adaptations were required in order to meet the building industry level of technology and pricing.

After four years of hard labor, great risks on many frontiers, intensive engineering and production experimentation, an entirely new generation of shell structures was born through the development of Yitzhak Rabin Center roofs. It inspired other architects and initiated possibilities for other wild architectural ideas like the Mediateque in Pau, France, designed by architect Zaha Hadid in London. She proposed to make the shell structures black instead of white. This choice of color would lead to carbon fiber epoxy sandwich shells rather than glass fiber composites shells. If required, a seamless skin for this much bigger

project than the project described in this book, would require an immense temporary shed build over the permanent building in order to cure the CFE composites. The European tender for this highly experimental structure without any experience on the design side nor on the production side, was fortunately for all parties involved cancelled in time.

We hope you will enjoy the content of this book, which extensively and openly describes considerations and challenges in all phases from tender to on-site creation of this beautiful well-executed innovative world novelty Yitzhak Rabin Center project.

The book contains chapters which are arranged in the chronological order of processing the project with an extra post-process chapter of the lessons learned from this experimental project which almost lead into a new experiment, aborted just in time.



01 STARTING POINTS AND TENDER

In November 2002 the 'Friends of the Rabin Center' issued the tender drawings and specifications prepared by world-renowned architect Moshe Safdie to design & build the roofs and the glass facades for the Yitzhak Rabin Memorial Center in Tel Aviv.

The building is a national institute, which was commissioned by the Knesset in 1997 in order to advance the legacy of the late Israeli Prime Minister Yitzhak Rabin. Rabin was assassinated in a peace rally in Tel Aviv in November 1995, after being rewarded the Nobel Peace Prize together with his compatriot Shimon Peres.

The Rabin Center was designed to be an educational center, promoting peace, human rights and democratic values. With architecture consisting of a museum, a library and halls, the building was designed to host exhibitions, charity galas, conventions, lectures and other educational events.

The building is located on top of an extension of a former auxiliary electricity plant near the Tel Aviv University campus. This post-war bunker has two-meter thick reinforced concrete walls and contains five huge turbines, which could supply the entire city of Tel Aviv of electricity in case of war; a fact that very few people are aware of.

The architectural and cultural significance of the project, identity of the designer and the other prominent parties involved in its creation, were very promising as far as Octatube was concerned.

The design architect for the Rabin Center was revealed to be Moshe Safdie, CC, FAIA an acclaimed architect, urban planner, educator, theorist, and author. Safdie is world famous for his well-thought, often dramatic designs. Born in Haifa, Israel, in 1938, Safdie moved to Canada with his family at a young age. He graduated from McGill University in 1961 with a

degree in architecture. After apprenticing with Louis I. Kahn in Philadelphia, Safdie returned to Montreal to oversee the master plan for the 1967 World Exhibition. In 1964 he established his own firm to realize Habitat '67, an adaptation of his thesis at McGill, which was the central feature of the World's Fair and a groundbreaking design in the history of architecture.

Safdie has been the recipient of numerous awards, honorary degrees, and civil honors, including the Companion Order of Canada, the Gold Medal of the Royal Architectural Institute of Canada and the 2015 American Institute of Architects Gold Medal. His designs include a wide range of projects: cultural, educational, and civic institutions; neighborhoods and public parks; mixed-use urban centers; airports; master plans for existing communities and entirely new cities around the world. Safdie has worked with a wide range of clients, including municipal entities and government agencies, colleges and universities, private developers, and non-profit organizations and civic institutions. Many of his firm's buildings have become beloved regional and national landmarks, including Marina Bay Sands, Singapore; the Jewel, Singapore; Chongqing Chaotianmen, Chongqing, China; Exploration Place Science Center, Wichita, Kansas; Salt Lake City Public Library, Salt Lake City, Utah; Peabody Essex Museum, Salem, Massachusetts; Springfield Federal Courthouse, Springfield, Massachusetts; Skirball Cultural Center, Los Angeles, California; Lester B. Pearson International Airport, Toronto, Canada; the National Gallery of Canada; Yad Vashem Holocaust Museum, Jerusalem, Israel.

Safdie is also responsible for major segments of the restoration of the Old City of Jerusalem and the reconstruction of the new center, linking the Old and New Cities; and for the design of six of Canada's principal public institutions, including the Quebec Museum of Civilization, the National Gallery of Canada, and Vancouver Library Square.

In addition to numerous articles on the theory and practice of architecture, Safdie has written several books, most notably, *Beyond Habitat* [1970], *For Everyone a Garden* [1974], *Form and Purpose* [1982], and *Jerusalem: The Future of the Past* [1989]. *The City After the Automobile* [1997], details Safdie's ideas about urbanism and city planning. A comprehensive monograph of his work, *Moshe Safdie I*, was published in 1996. *Moshe Safdie II*, a second monograph featuring work from 1996-2008, was published in 2009.



FIG. 01 Habitat from 1967, designed by Moshe Safdie
[http://en.wikipedia.org/wiki/Habitat_67#mediaviewer/File:Habitat_panorama.jpg]



FIG. 02 Habitat from 1967, designed by the young Moshe Safdie
 [https://en.wikipedia.org/wiki/Moshe_Safdie#/media/File:Montreal_-_QC_-_Habitat67.jpg]

From [Wikipedia](#): After apprenticing with Louis Kahn in Philadelphia, Safdie returned to Montreal to oversee the master plan for Expo 67. In 1964, he established his own firm to undertake Habitat 67, which pioneered the design and implementation of three-dimensional, prefabricated units for living. It was a central feature of Expo 67 and an important development in architectural history. He was awarded the 1967 Construction Man of the Year Award. In 1970, Safdie opened a branch office in Jerusalem. Among the projects he has designed in Jerusalem are Yad Vashem and the Alrov Mamilla Quarter, which includes the Mamilla Mall, David's Village luxury condominiums, and the 5-star Mamilla Hotel. In 1978, after teaching at McGill, Ben Gurion, and Yale universities, Safdie moved his main office to Boston and became director of the Urban Design Program at Harvard University's Graduate School of Design, until 1984. From 1984 to 1989, he was the Ian Woodner Professor of Architecture and Urban Design at Harvard. Since the early 1990s, Safdie, a citizen of Canada, Israel, and the United States, has focused on his architectural practice, Safdie Architects, which is based in Somerville, MA and has branches in Toronto, Jerusalem, and Singapore. Safdie has designed six of Canada's principal public institutions as well as many other notable projects around the world, including the Salt Lake City Main Public Library, the Khalsa Heritage Centre in India, the Marina Bay Sands integrated resort in Singapore, the United States Institute of Peace headquarters in Washington, DC, the Kauffman Center for the Performing Arts in Kansas City, and the Crystal Bridges Museum of American Art in Bentonville, Arkansas.

This was Octatube's second collaboration with Moshe Safdie: the first one being the glass cone of the Samson Centre in Jerusalem, overlooking a valley adjacent to the old city near the Jaffa Gate. This Samson center is located opposite to the Jaffa gate. In the later part of the afternoon, when the sun is setting, golden light shines on this part of old Jerusalem and its Jaffa gate buildings has a very romantic atmosphere [fig. 04]. Safdie is an almost prophetic designer who designs beautiful interior spaces. He redesigned the Jewish quarter in Jerusalem and the dramatic Yad Vashem Museum in Jerusalem, on the Holocaust. Dramatic as the space is a high arch running in one line of over the museum spaces, making the space with natural concrete finish very sober and aligned. The Samson glass dome, overlooking the ancient city with its golden color in the afternoon, is used for marriage feasts and other celebrations and is a great success. The hall is used for weddings twice a day. Safdie was very satisfied with Octatube's alternative design proposals and with the realized accuracy.

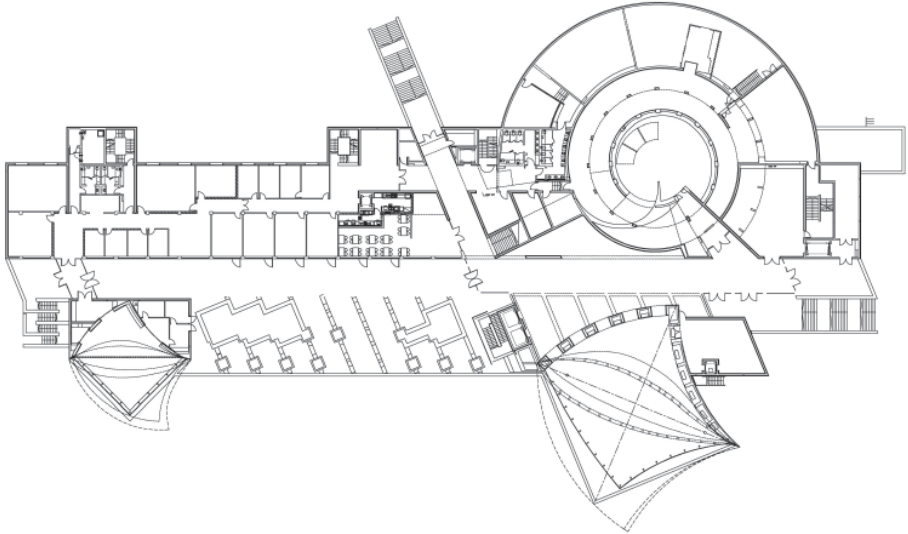


FIG. 03 Plan of the Rabin Center, Tel Aviv [courtesy: Moshe Safdie & Associates]

The project's tender provided for two building parts: the 'Great Hall' and the 'Library'. These two big rooms both have large glass façades facing south towards the HaYarkon valley below. Both hall designs feature remarkable designed roofs. The wing shaped roof of the Great Hall was designed to resemble a dove: an internationally recognized Jewish symbol of peace, as a tribute to Rabin's efforts for peace [fig. 05].



FIG. 04 Samson Centre in Jerusalem

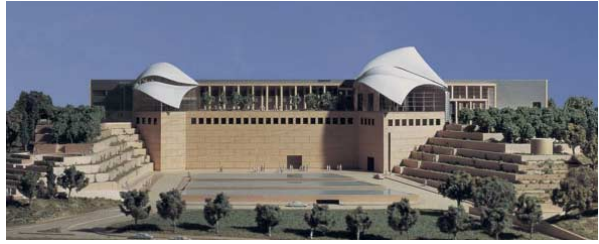


FIG. 05 Architectural model of the Rabin Center, Tel Aviv [courtesy: Moshe Safdie & Associates]

The complicated liquid design roofs of the Rabin Center contained in the tender, were analyzed by ARUP of New York and to be made of a system of arbitrary open steel profiles with a layer of reinforced concrete on top [fig. 06]. The steel structure was not very systematic and hence the invitation was not very promising for the tendering parties. The specifications left the specification of the concrete roof cladding up to the contractors. On top of this the architect requested a seamless solution for the finished roof. Not a very appealing specification for a Design & Build company that had to transport all items over a distance of more than 5.000 km.

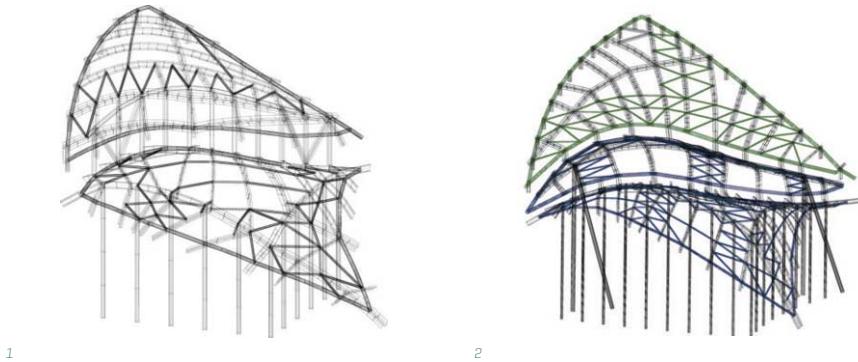


FIG. 06 Tender drawings made by ARUP. Left, 'The Library' and right, the Great Hall.

For two months the tender drawings and the thick specification were not given much notice. The 'seamless' requirement would make any prefabricated system very difficult to apply and the success would depend entirely on local labor and supervision, which a producer of industrial and prefabricated systems is not used to and his whole production discipline is not geared to do either. However, the client and his building manager kept on reminding of the tender date.

THINKING AND REASONING BEFORE THE RABIN CHALLENGE.

Around the time of the tender stage of the Rabin tender, Eekhout struggled with an alternative technical design of a new cladding for the Atomium of Brussels (dating from 1958), two of his colleagues, TU Delft's professors Adriaan Beukers and Michel van Tooren from the Faculty of Aeronautical Engineering, stated in their inaugural lectures that "aeroplanes always leak and condensate" [Beukers, 2003; van Tooren, 2003]. Indeed it was well known that the Atomium had always leaked and was full of condensation (fig. 07).

This sentence inspired Mick Eekhout to undertake a quest for a re-cladding concept of the 9 spheres of the Atomium. The end result was that in the technical proposal each of the 18 m diameter domes was to be clad with 2×8 spherical segments, each in the form of half an orange peel and with a size of 14 m long, 8 m wide and 3 m curved out of plane. These segments were supposed to be made in glass fiber reinforced polyester with an aluminium gel coat in its outer surface (fig. 08).

When the segments were eventually placed in a mould to be vacuum injected, it became clear that it would be possible to place stainless steel 3D-curved segments in the mould, build the complete package on the mould and suck the polyester into the components. This idea of large sized panels resulted in only 20% of the joint length, which originally was 20.000 m'. Even a low leakage percentage of 1% would still result in 100m' of leaking upper seams. The lower seams would leak outward and do no harm. In the developed proposal 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. Leakage problems would belong to the past with this solution. Transport of these 8.0m wide, very large components seemed possible over water. A patent was applied for. It was a silicone free, low maintenance solution. The impulse from aeronautics helped Eekhout and his team to develop a new concept. Alas the contract for execution was awarded to a Belgian party (fig. 09). The design proposal keeps its value, leading to inspirations to further projects.



FIG. 07 Close-up of the old Atomium, Brussels.



FIG. 08 Schematic drawing of the proposed division: 2×8 spherical segments in GRP



FIG. 09 The renovated Atomium

One year before the tender stage of the Rabin Center, the design, engineering and building of the Municipal Floriade pavilion (now named 'Hydra Pier') of Asymptote Architects from New York was completed (fig. 10). This project contained 3 experiments: Firstly in the façade cold bent glass panels each $2 \times 2 \text{ m}^2$ cold, bent in a curve of 200 mm radius. The second was a frameless glass belly of 1400 mm deep, filled with water, running continuously from the top of the building into the water pond and spilling over its edge over glass panels. This happened on two opposing sides, so one could walk to the entrance of the building like Moses through the Red Sea.

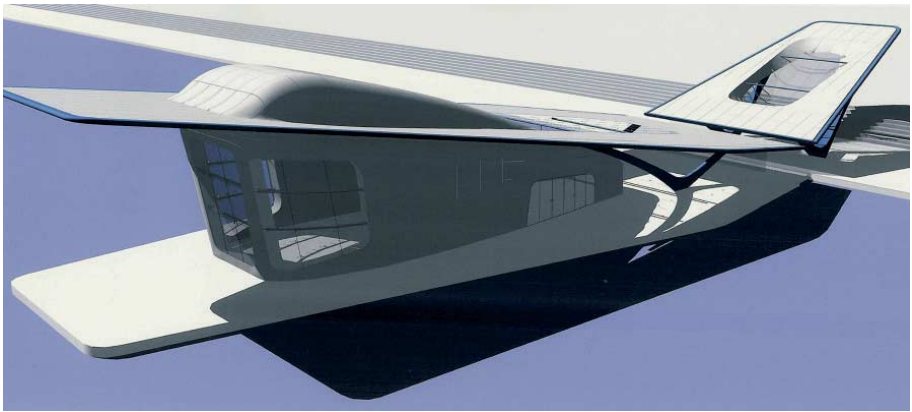


FIG. 10 Overview of the Floriade pavilion in Hoofddorp NL

The third and last experiment consists of 3D-aluminum panels with a thickness of 5 mm and in a free form shape. They were deformed through TNT-explosion on negative concrete moulds [based on machined positive polystyrene moulds]. This production process originally seems to have been used for the noses of Russian submarines in the 1960s. The paths of technology transfer are sometimes strange. The explosion process took place

at Exploform bv in Delft. This complete production procedure from engineering drawings, via Styrofoam negative moulds and reinforced concrete moulds, the explosion process [fig. 14], the measuring and fitting on timber moulds up to the finished and installed watertight and coated panels proved to be a feasible, but also a laborious process to fabricate as 3D-curved panels [fig. 11-15]. It was the first time in the world that 3D-aluminium panels for architecture were produced along these complicated paths. Although we successfully made this Floriade project, the m² price of the 3D-curved panels was too high for a commercially sound next project in the building industry, which was on the verge of a recession at that time. Nevertheless the process followed was realistic enough and produced an excellent end result [fig. 16, 17].



FIG. 11 Left over polystyrene moulds used to make negative concrete moulds



FIG. 12 Exploformed aluminium panel with welded edges



FIG. 13 Fitting of a panel on a wooden fitting mould



FIG. 14 Video captions of an 'Exploform explosion' in a water basin (from: exploform.nl). The TNT explosion took place in a water basin, which compressed a flat aluminium plate into a concrete mould below, while the water jumped 20 m high



FIG. 15 Detail figure of Floriade pavilion, Left side model

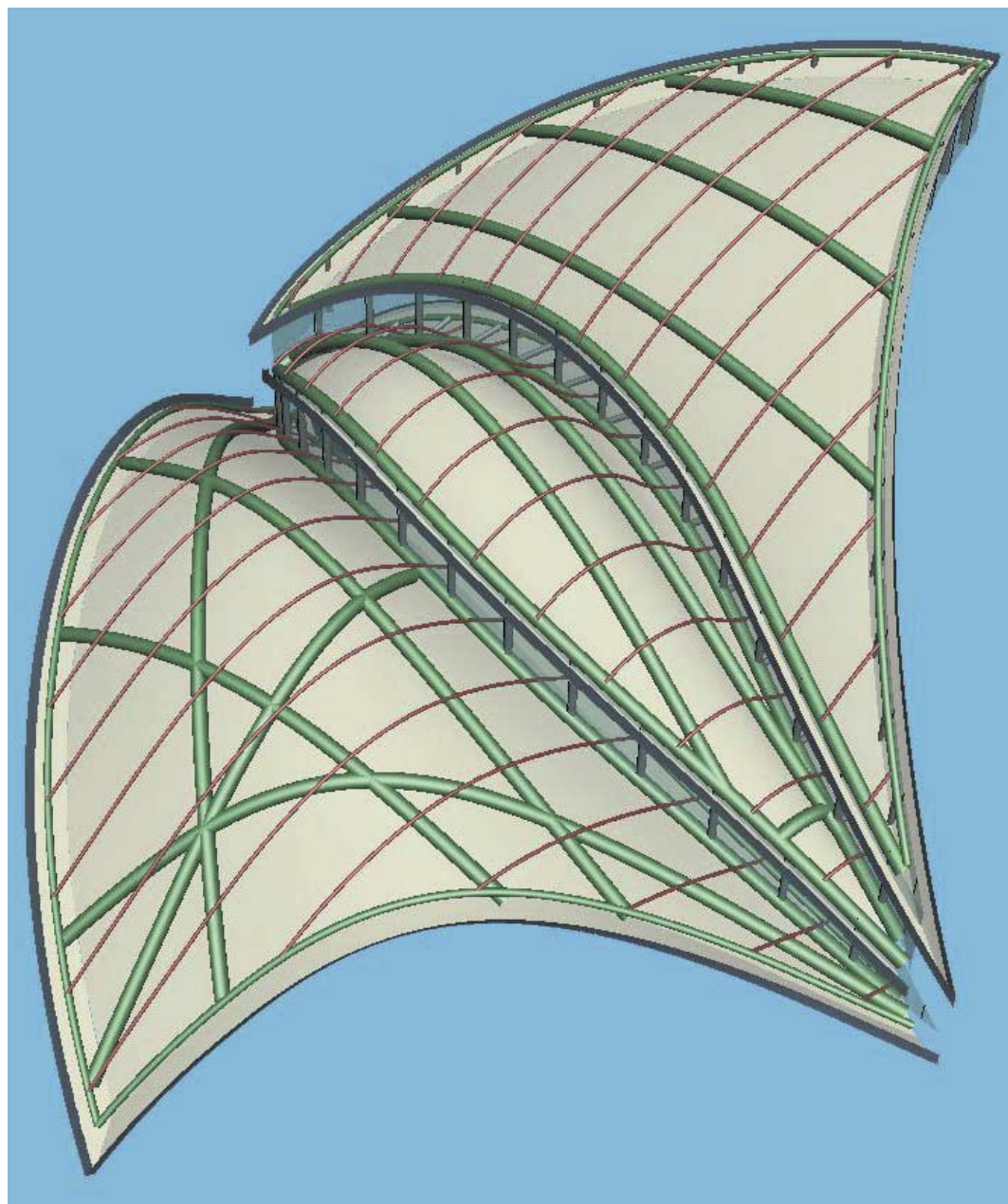


FIG. 16 3D curved roof of the Hydra Pier



FIG. 17 Detail photograph of the assembly of the complete corner of the aluminum panels

A cheaper system had to be developed for the next project, which was the Rabin Center project in Tel Aviv, Israel. Haiko Dragstra, a very inventive mechanical/electrical engineer with his company Complot, Delft, co-operated in this project and came up with the idea to take thinner sheets of aluminium, laminate a foam panel with parallel transverse sleeves and an epoxy laminate as the inside skin in order to make a strong and stiff panel. One step further was to make the complete panel out of two composite skins with a foam core and have the outside skin coated, if needed in an aluminium metallic colour. One does not see the difference from painted aluminium or steel panels and polycarbonate components in cars. However, at the time Asymptote Architects as designers for the Hydra Pier pavilion, did not like the idea of mixing different materials, according to the contractor. It was this line of thinking that brought the development further. Dragstra was able to machine foam blocks into any desired form by the machines he built himself. Machining according to CAD data is possible both for the top and bottom layer of the foam. The total surface of the roof subdivided in parts, would consist of machined foam blocks that were glued together to form the roof shell. Subsequently structural layers of glass fiber reinforced polyester were applied to each side. These experiences came along during brainstorming sessions on the new principles for the 3D-curved wings of the Rabin Center. Innovation often takes place in small steps ahead, incremental innovations, so that each step is carefully done and investments are not too large for a small SME company. The described innovative steps are seen in sequence of improvements, one on top of another, until a real innovation has been developed and which stands its grounds in the building industry. In the conclusion we will refer to the success of this composite sandwich wings adventure.



02 THE TENDER PROPOSAL

After Moshe Safdie's office had postponed the tender date for 2 months in order to tempt Octatube to participate in the tender with their own proposals, the real thinking in the heads of the designers and engineers of Octatube started. Now the dream of Safdie became the challenge for Octatube. We had experienced two prior projects with free form panels: the free form roof hatches of the 2002 Floriade pavilion and the perfectly spherical segments for the Atomium in Brussels. The Rabin roofs were exceptional as there was no repetition at all in the overall free form geometry of each of the roofs. On top of that, they were five very large wings of which the largest was about 20 x 30 m², which a height of approximately 11 m, when placed on its tips on a horizontal surface. Exploding aluminum panels was expensive. The architect expressed his desire for a seamless finished surface, as abstract as possible. So separate panels were doomed and the quest continued.

GIANT STRESSED SKIN SANDWICH CONSTRUCTIONS

After a few brainstorm sessions, the basic idea was as follows: make the roofs as giant surfboards of foam with stressed GRP skins on both sides. The 5 shells composing both Library and Great Hall roofs, were each very large and measured up to 30 x 20 x 11 m. The composites company Polyproducts of Werkendam, NL, was invited to join the tender team of Octatube, as well as mechanical engineer and inventor Haiko Dragstra. Over the period of about one month, three successive brainstorm sessions were organized on the product idea, the structural concept and the logistics & pricing. It was decided to work out and price the revolutionary stressed sandwich skin alternative as well as the original tender specification of the steel structure with a non-described, free covering as a variation. The steel deadweight of the steel structure was estimated by ARUP, so a price of the original design with the steel structure, supposed in an alternative form of curved CHS [circular tubes] with cladding variations in different foam, leveling and top layers was easily provided. The cladding proposed for the original tender design was derived from the mega-sandwich idea, but now in a thinner scale version of 50 mm sandwich thickness, as it only needed to span the space between the steel structure elements [which was max. 3 m].

The budget calculations came out on a level of 2,5 million € for the original design, inclusive of a thin 50 mm thick GRP sandwich cladding instead of concrete. This total price would not only contain the roof wings, but also the glass facades and claddings. The alternative design with the full load bearing stressed skin sandwich would add up to more than 4 million €, largely due to the high estimates of the production of the polyester parts. The producer had never done a project of this magnitude but knew how to operate the production of sandwich panels using vacuum infusion methods. It was argued during brainstorm sessions, that the maximum extra costs could not exceed the sum of one million € extra, resulting in a total alternative price of 3,5 million €. Yet it was a risk, as alternative proposals are usually cheaper than originals.

It was foreseen that any modernist architect would fall in love with the alternative idea of the self-supporting stressed skin sandwich. This was the solution faxed to Israel, just in time before the tender closing date, accompanied by a letter explaining the two quoted systems: the original scheme with a variation in a steel tubular structure with a sandwich roof and ceiling and the alternative solution of the giant surfboard-like stressed skin sandwich panels [fig. 18-21].

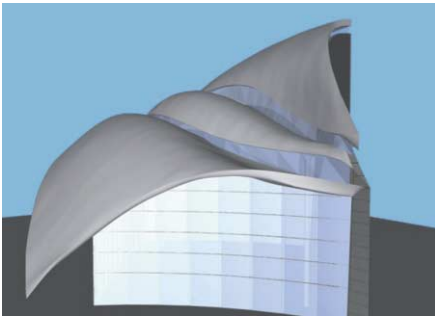


FIG. 136 The Rhino model of Moshe Safdie & Associates



FIG. 137 Model of Library



FIG. 138 Wireframe model of Library

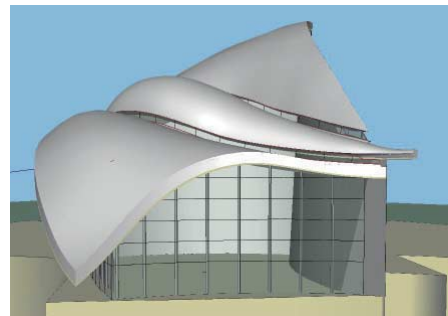


FIG. 139 The first tender redesign in Maya by Octatube

In the course of the tender design development the rough contours of the roof wings given in the tender stage by the Safdie office had to be redesigned. These were handed over from Boston as a Rhino model, generated from a 3D-scan from a material 3D-scale model. The data within this model needed converting, since its meshed geometry proved to be unsuitable for further engineering. Through analysis of different cross sections of the model and connecting these in fluent lines, a better usable 3D-surface model was developed. The ensemble was redesigned in Maya [3D CAD software] software, which turned out to be an excellent medium for controlling the overall redesign of the roof shells, glass facades and supporting steel structures as well as designing the different components within each system. Hence, the software enabled us to define the constituent parts and to combine and review them into the total composition [sandwich roof wings, columns, glass strips and glass façade panels]. The design also included the complex shape of the reinforced concrete walls, the cast-in situ support plates of the concrete tops for anchoring of all short & long columns.

AMAZING SOLUTION!

Only two days after the tender date was closed we received a telephone call from the local representative architect Zachi Halberstadt, speaking on behalf of Moshe Safdie. He gave us the compliment that Safdie saw the alternative proposal as “an amazing solution”. Mr. Halberstadt invited Mick Eekhout to come over to Tel Aviv for a meeting immediately, so the idea could be presented to the building commission. The polystyrene models for internal brainstorming were already redesigned, machined, built, used in our brainstormings and waiting to travel light. At the meeting the next day, the polystyrene models that Haiko Dragstra had machined for a demountable 1:40 scale model were presented (fig. 19). The models showed that the corner details in the design had not yet been accurately designed and that the overall stability was not satisfactory. The proposal still needed a lot of design & engineering work, but the enlarged scale model did show the serious interest of Octatube in this tender.

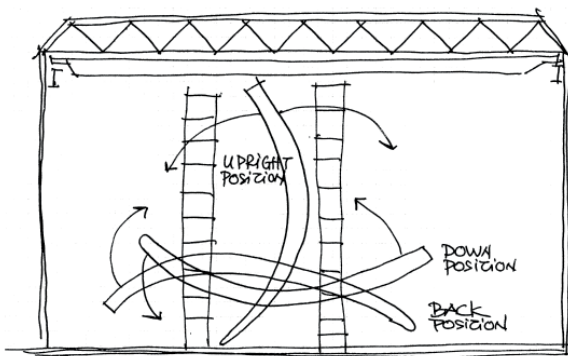


FIG. 22 Schematic drawing of a shipyard building with roof-wing positions

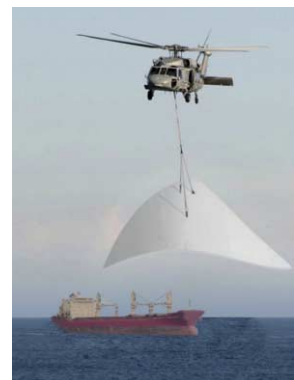


FIG. 23 A 'wing' transported by helicopter (photomontage)

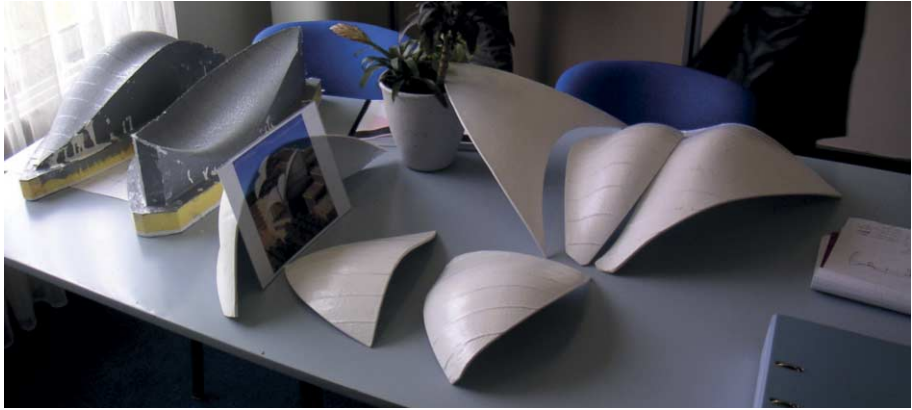


FIG. 24 The making of GRP scale models

The building commission was astonished after hearing the explanation of the construction and the consequential logistics of the alternative proposal. The big wings would have to be constructed in one of the empty ship building halls in the Netherlands, like the empty ship wharf hall of Hollandia at Krimpen aan den IJssel. This size of hall was necessary as the wings would have to be turned upside down after application of the stressed skin layer on one side in order to apply the stressed skin on the other side [fig. 22]. Remember the wings are 11m high at the most. We would move the milling polystyrene machine nearby this production hall and install it adjacent to the assembly area. After gluing of the polystyrene blocks, the top skin could be applied. That is, if the polystyrene blocks would form a roof wing in a more or less horizontal position. After completion of the GRP top skin, the object had to be turned as mentioned, such that the bottom skin could be applied. After the completion of all shells, they would be loaded onto an open inland vessel and towed to the port of Rotterdam, where the 5 finished shells would be vertically stacked on a specially chartered ship. This ship would sail to Tel Aviv and anchor at sea in front of the city [fig. 23]. From this location a giant freight helicopter (no doubt of the Israeli army) would lift the roof wings individually 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 to which they would be fixed. The whole shipment and air transport was pretty special and expensive. By the way, the name of the vessel in the picture was the 'Oslo', which gave some unintended hints to the failed Oslo peace talks of Yitzhak Rabin.

After explanation of the logistics of this alternative proposal, the Israeli Octatube representative Boaz Brown heard the architect Moshe Safdie mention to the chairman of the building team in Hebrew: "you should try to get the one million extra" or words of that meaning. So there was surely enthusiasm.

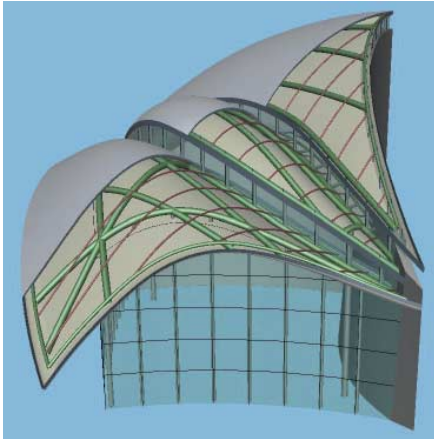


FIG. 25 A steel structure of CHS circular sections [a variation on the original tender specification]

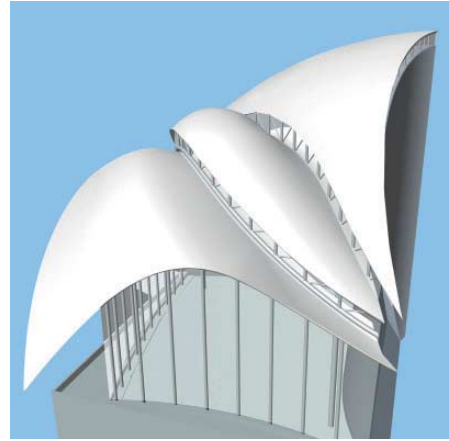


FIG. 26 The structural sandwich structure [the alternative tender proposal] for the Great Hall

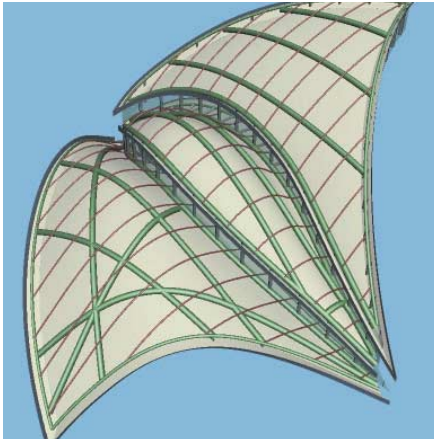


FIG. 27 Steel structure with ceiling panels only



FIG. 28 Structural sandwich for the library

CLIENT: "EXTREMELY INNOVATIVE, BUT EXPENSIVE"

The building commission went into a separate meeting. After one hour of fierce discussions, the outcome was that the original tender with Octatube's proposal to apply the steel tubular structure and the thin GRP covering turned out to be on the average tender price level (fig. 25). On the other hand they noted, that the alternative proposal with the composite sandwich constructions was indeed very attractive based on its extremely innovative design and construction, but was priced one million € over budget (fig. 26). Knowing the intellectual value of the alternative proposal, it would have been stupid for Octatube to sell it at a lower price than the tender proposals. The higher price for the highly

innovative proposal contained of course some contingencies for the many uncertainties. Usually technical alternatives are more efficient solutions for the contractors and tend to be lower in price than the original. A more expensive alternative is rare and hence extraordinary. Starting with the highest price and the best technology may end with a contract at a compromised price. A designer also loses projects to competitors as they can copy the new technology after one completed project and execute this without the necessary research and without the higher Dutch labour costs of Octatube. In our case of the wings, the alternative idea was to become a technical world novelty and Moshe Safdie understood this.

EXAMPLE OF THE SYDNEY OPERA HOUSE

The discussion at hand with Safdie was about the Sydney Opera House (built in the 1970-ies) and how lucky architect Jørn Utzon would have been if he could have used stiff GRP sandwich panels instead of the heavy concrete shells and ceramic tiles (fig 29,30). Even though the realization of the Opera House meant a giant step in the history of structural engineering, the marketing concept of Octatube's tender idea of giant surfboard plans for the Rabin Center would have worked.



FIG. 29 Sydney Opera House, architect: Jørn Utzon

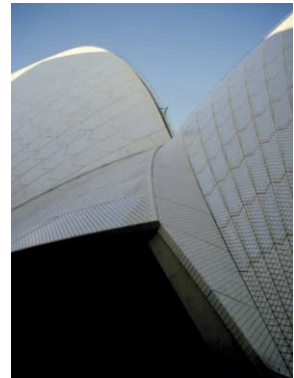


FIG. 30 Detail of the same

Safdie appraised his belief in stating that he thought that the idea was unbelievable and never done before to his knowledge. If someone could make it work in his opinion, it was to be Mick Eekhout. The response of the chairman of the building committee was to come up with different logistics for the GRP sandwich proposal in a manner that the price level could be lowered to 2,5 million €. He suggested that it might be possible to transfer the foam machining and the GRP production to Israel in order to reduce costs for shipment and labour at the same time. This was the message taken home on 29th of April 2003.

RETHINKING THE ALTERNATIVE TO BE MADE ON SITE

The overall strategy forward was born on the airplane back from Israel to the Netherlands. Back in Delft the consequences were discussed with our in-house engineers and the external team members of co-makers. If the GRP sandwich roofs could be realized, it would be a novelty on the world market. The alternative with the steel structure and the thin sandwich skin wrapped around it would be our 'plan B' in case the composite sandwich construction appeared one bridge too far. We had to reorganize ourselves, by transferring more labour to Israel in order to reduce cost. To accomplish this, we had to talk to new Israeli partners in order to realize the project, in case the current partners got cold feet and might let the project down. First idea was to try to decompose the big wings into transportable segments, which could be assembled on a jig on-site in order to finish the interrupted GRP layers at the seam locations and give the shells the final smooth top-layer or top-coat, just as smooth as Moshe Safdie would want to see it. Heiko Dragstra of Complot could ship his machine in a container to the building site and machine the polystyrene blocks locally. Polyproducts in its turn could set up an Israeli GRP plant in Tel Aviv on the building site as well. The most likely position to assemble a wing would be in a more or less vertical position.

This way both polystyrene skins could be applied and treated simultaneously using a hand-layup method and the shrinking of the foam could be controlled. Subsequently, the roof wing located between two 20 m high scaffolding towers, could be lifted by a mobile crane. As we write this book 10 years later, it displays the naivety of brainstorm sessions, but also the force to overwhelm whatever immediate drawbacks and objections came on the table. Architecture is a fantastic domain!

However, after a few meetings it appeared that machining the polystyrene blocks in Israel seemed very expensive. The subcontractor was not experienced in estimating larger productions than mock-ups. The calculations on the bottom price of Polyproducts in Israel did not give much hope either. At the same time the usual squeezing of tender prices came about, which forced the sales department to land on another price level altogether.

For the sake of financial negotiations, yet another point of view had to be taken in. It was decided to put all first emphasis on the original design with the internal steel structure and sandwich coverings, our Plan B. Hence we continued with an internal and hidden steel space frame and applying a locally made sandwich panel system on top and bottom, forgetting for a moment the attraction of the possible world novelty of the stressed skin sandwich constructions, just to stay in the race. Based on this price and on the technical abilities Moshe Safdie was convinced that Octatube could do the best job. Therefore Safdie pressed the client to take a wise decision: to issue an (experimental) pre-engineering contract to execute the design development and make material prototypes for the much wanted sandwich stressed skin principle.

Negotiations with the client had resulted in a substitution change of the subcontractor alias co-maker for the polyester work. The price level of Polyproducts remained too high and they were thanked for their collaboration. We invited Holland Composite Industrials

[HCI, based in Lelystad, NL] in their place. They had previously made hulls of motor yachts and sailing yachts in glass fiber reinforced polyester (GRP) up to 30m length, using the vacuum infusion method. Director Pieter-Jan Dwarshuis was a graduated industrial designer from TU Delft, able to think analytically and yet full of motivation to undertake novel designs. Their 3D-experience proved to accelerate the thinking of the project [fig. 31]. This was an excellent starting point for the development of the structural sandwich panels. HCI collaborated regularly with the engineering firm Solico Engineering (based in Oosterhout, NL) who had ample experience in structural analysis for composite components in naval architecture. They first started with the analysis of the GRP roofs on a global scale. The two preliminary independent structural analysis reports of Octatube Engineering and Solico Engineering were compared and “luckily” matched. Sound engineering thinking is a virtue and gave us trust in that respect.



FIG. 31 Composite segment production on moulds at the factory of Holland Composites in Lelystad

It was the hope of the client and the architect that the original quotation could be reduced thanks to the results of and new insight gained by the pre-engineering contract activities. For Octatube and its co-makers the preliminary contract was a method in which they could familiarize themselves with the resulting production method of vacuum injection and its uncertainties. This prototype contract could give the co-makers some experience with the engineering route to be followed, the structural system, the production method and the assembly and installation consequences. If all of those uncertainties would be revealed, the making could be re-calculated as more realistic and offered as a final price to the client.

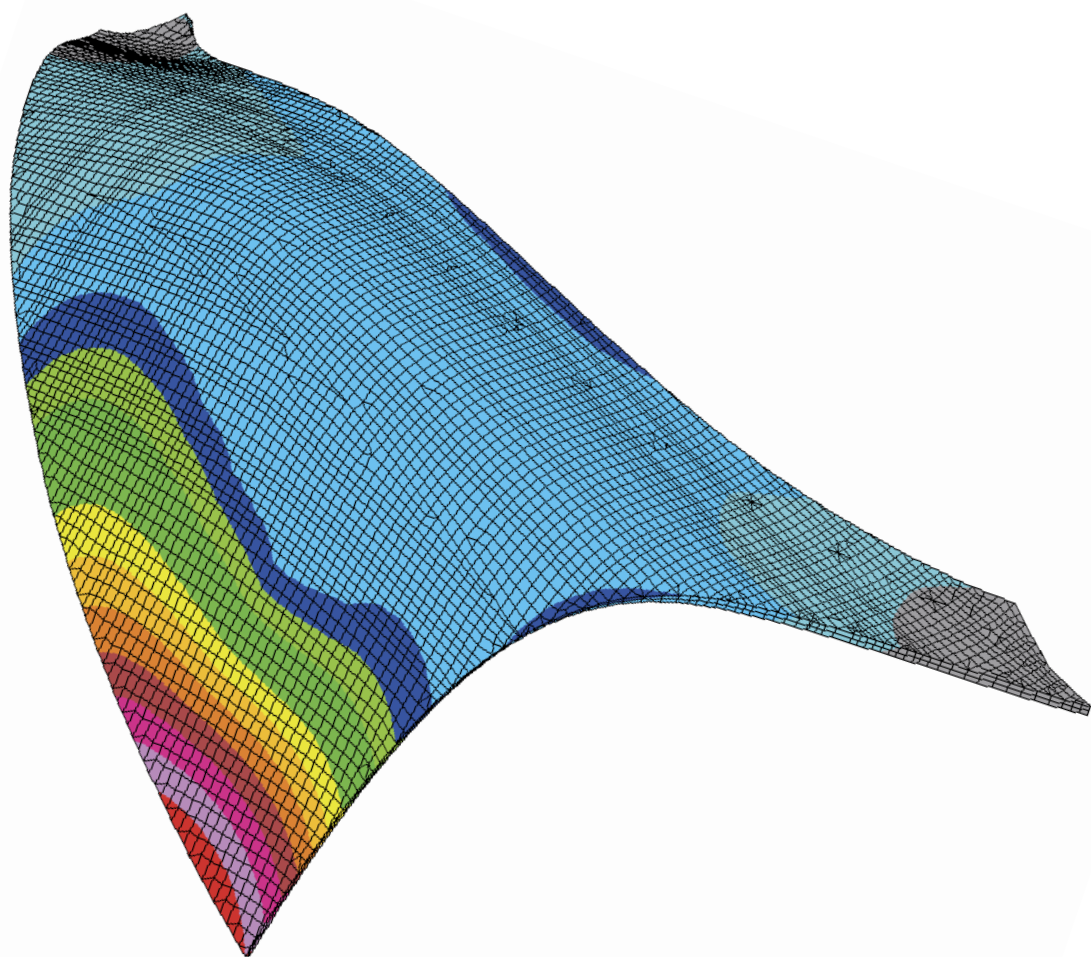
This pre-engineering contract was a wise decision, which we often advocate in the Netherlands for experimental projects, but which we unfortunately hardly ever receive.

Innovation and experimentation should take place separate from real building projects, otherwise accidents or grave disappointments may happen. In the past we received an order for a 27 m long exterior glass beam spanning between two building parts at 25 m height, composed of annealed glass, which we had to develop as a prototype [Swiss Life in Amstelveen]. We did not take the design responsibility over from the project engineer and we stated clearly this, while making efforts to make it work by alterations and improvements. The development work took 3 full years, we started when the main contractor started his piling foundations and ended after the building was completed. The structural parts were not reliable enough and the project was aborted when 90% of the project budget was consumed for research & development. At that time the building was already in use and it became the only 'failed' project of Mick Eekhout to date.



FIG. 32 Rendering tensegrity structure Grote Marktstraat Den Haag 2013, Arch. Lana du Croq

Other projects that failed at the tender were the carbon fiber reinforced epoxy roofs described in chapter 8 of this book [Pau, France] and a complex tensegrity structure of 500 poles and 2500 cables, suspended above the busiest shopping street in The Hague. Latter was tendered as if it were a typical building project, however it seemed impossible to build [fig. 32]. The project was cancelled before the tendering process was completed. In both of Pau and The Hague it would have been wise to include a small prototype phase before tendering and publish its results, so that a learning curve from the engineering, production and installation would be available to all at the time of tendering. Often architects think that anything they draw on the computer can be built. Free form designers hardly had any experience at the turn of the millennium, so no wonder that liquid designs were regarded by contractors as 'free form nightmares'. On top of that, free form production technologies of contractors lagged far behind free form phantasies of architects. Clients fear monopolization during tendering and prefer to go for a European tender instead of a pre-prototyping contract. Which makes experimentation virtually impossible.



03 PRE-ENGINEERING AND PROTOTYPING

Following the advice of Moshe Safdie a contract was agreed to make two samples: one for Plan A (composite sandwich structure) as per fig. 26 and one for Plan B (steel structure and sandwich cladding) as per fig. 25. This allowed us to start with the free form development of both roofs and to end with prototypes including some of the components in order to show their structural behavior, production method and aesthetics. The designing process went into design development and prototypes for the construction of the Great Hall, understanding that the Great Hall would be far more challenging than the Library and assuming that the principle details of the Library structure would follow those of the Great Hall. Yet, in the executed production sequence it was the smaller Library structure to be the first as a 'zero-production' to learn from and to be followed by the larger and more complex Great Hall. The client had another idea: first to build the Great Hall and when they would run out of fund they were willing to forget the Library. This was not agreed by the architect.

ORGANISING CONCEPT DESIGN, PROTOTYPE DEVELOPMENT AND PRODUCT MANUFACTURING

The principle basic structural design was fixed by now as well as the preferred production method. The biggest hindrances of the experimentation seemed to have been overcome and the process streamlined into an official, experimental and innovative Octatube project. The process of development of the wings had to be carefully and strategically organized. 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 entire wings, all had a deep impact on the final design and had to be fixed by the responsible main contractor Octatube. Their influences were randomly taken up as the design development, testing and prototyping progressed. This type of highly innovative and sometimes revolutionary developments prove the Octatube adages of:

- Design and build in one hand;
- Integration of architectonic, structural and industrial design;
- Innovative development of new products.

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. The urge for new product innovation, courage, spirit of enterprise and a certain naivety (not to know on forehand what hindrances would come in the future years of development of the project), prepared the embedment of an engineering novelty with multiple degrees of innovation. The usual methodology used is given in fig. 33, 34 and 35. For more information reference is given to the book 'Methodology for Product Development in Architecture' [Eekhout, 2008]. In the conclusion of this book we will attempt to summarize its degrees of success and failure.

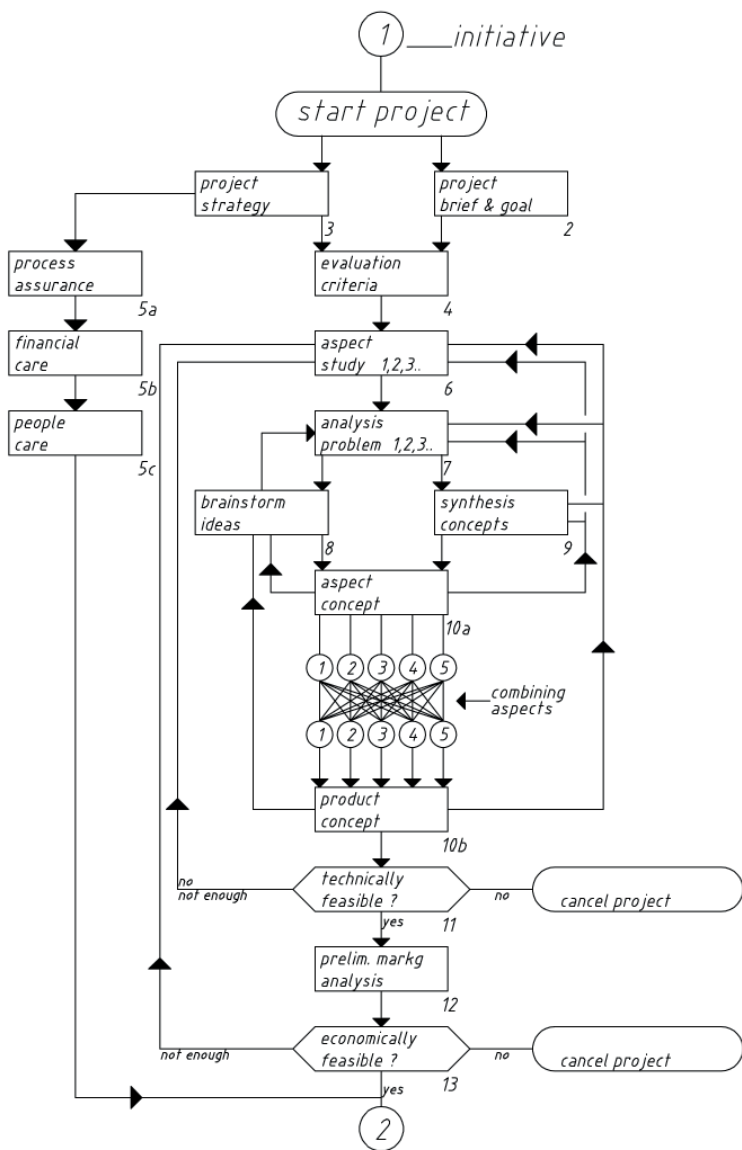


FIG. 33 Organogram Phase 1: Design Concept

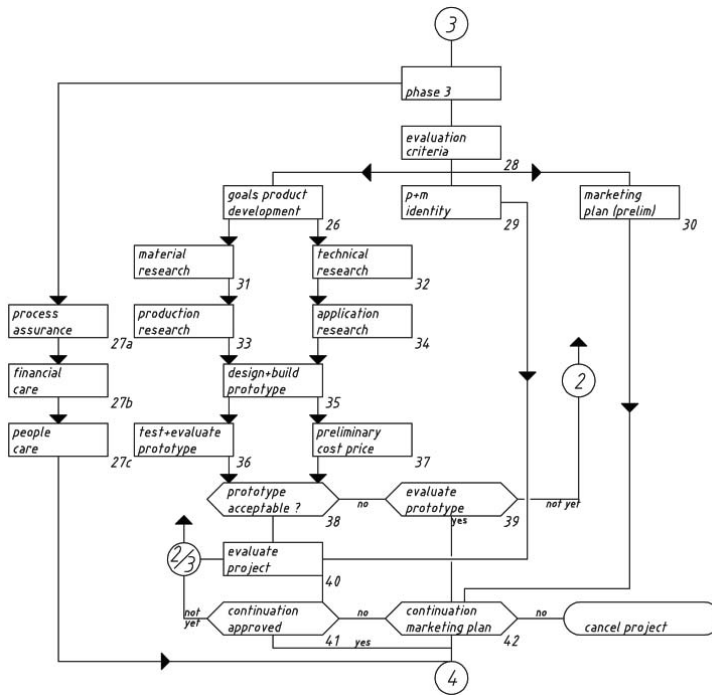


FIG. 34 Organogram Phase 2: Prototype Development

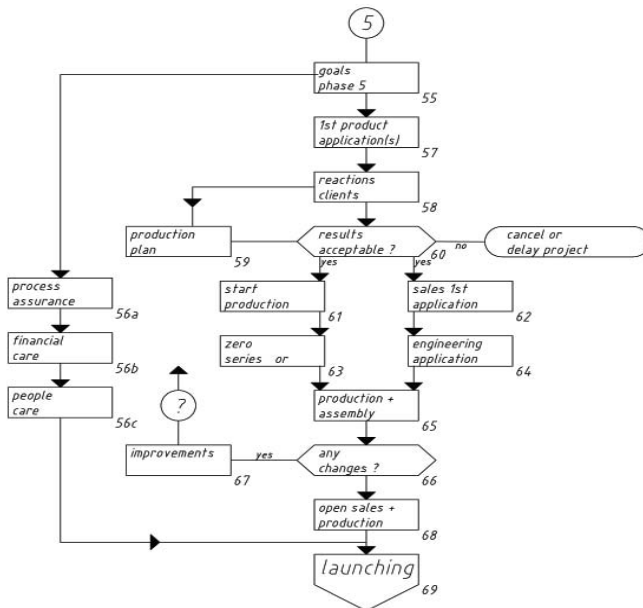


FIG. 35 Organogram Phase 3: Prototype Manufacturing

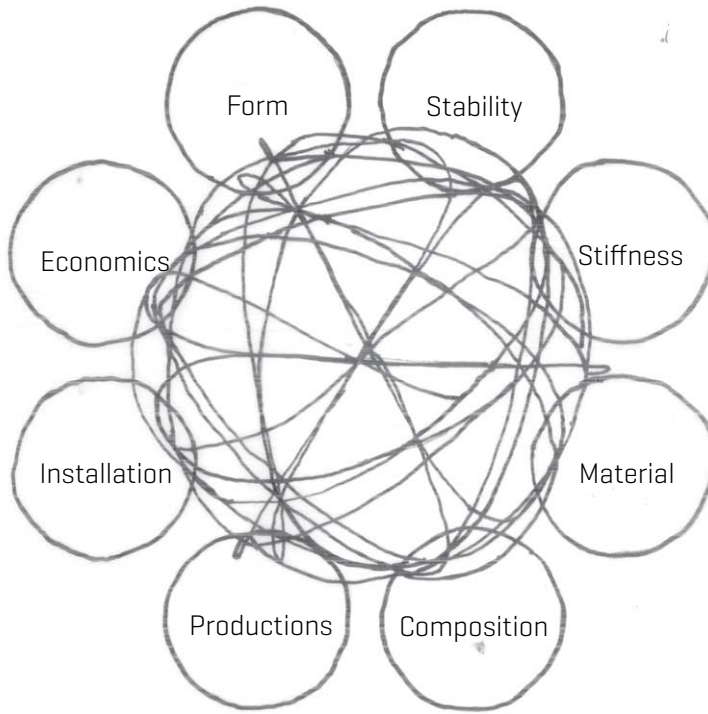


FIG. 36 Scheme of interrelationships during design

DESIGN IS A COMPLEX MATTER

The pre-engineering & prototyping order enabled the designers to revalue all relevant aspects. The order was performed at 4 major levels: [1] the prototyping of the structural principle, being the structural composite sandwich or the steel structure with composite covering, [2] the structural principles of the Great Hall as being the most difficult part of the contract, [3] the free form engineering of the composite wings and glass works and finally [4] the production of the composite sandwich structures, as our Plan A was preferred. These four levels are all related to each other and with other related aspects, which are given in figure 36. In order to reproduce a part of this pre-engineering and prototyping process, in which the architect showed great interest, this scheme is provided to visualize the random and often crazy making influencing of the different aspects on the design considerations. The interrelations represent the continuous feedbacks and connections one had to make in order to conquer a complete overview on the matter. In this case it was a preliminary design with proof of feasibility and technical designers looking at random for their 'Holy Grail'.

STRUCTURAL PROTOTYPING

At the same time a global analysis was made to confirm the structural behavior of the GRP wings and the steelwork. At this stage, both construction types Plan A and Plan B were still worked on: a steel structure of systemized CHS circular sections, covered with thin GRP sandwich as covering [Plan B: see figure 38, 39] and the designer's option of the structural stressed skin sandwich [plan A; see figure 40, 41]. The circular tubes can be bent in all directions using various radii and are engineered and manufactured to intersected neatly. From the centerlines of the tubular structure one could read where the largest forces were anticipated. In our case, this occurred at the corner column of the glass façade of the Great Hall, which supports the cantilever of the Lower Wing. The Central Body transformed into more of a central space spanning tubular frame. The composite sandwich alternative of our preferred Plan A works in a somewhat similar way of course,, although looking from the exterior one cannot see the tensile and compression stresses active in both skins of the shell, nor its active shear forces as they are not visually expressed.



FIG. 37 Mock up of 3 segments of the library wing in Lelystad, NL

It was decided to make a number of small prototypes in which we familiarized ourselves with the different construction options. The costs of the most favorite construction, the composite sandwich shell were still too high for the client, so initially our attention went to making the steel structure and a separate skin on top. In figure 38 and 39 two prototype are shown. In both cases there would be the load bearing steel structure, made of CHS profiles, bent in the desired directions and radii. This CHS tubular structure was covered with aluminium battens 20 x 50 x 3 mm, which were nailed onto the top and bottom side of the tubular steel structure. The battens would enable foam panels to be screwed on them with ~100 mm large washers. However, at the position of the screws, regardless of the use of oversized washers a dent was to be expected in the surface of the foam. That is why a second layer of foam was covering the first one, only fixed by glue along

its continuous surface and without dents. We saw that walking or kneeling on the foam surface was impossible without damaging the surface, so the top foam layer would need a protective epoxy layer with a light glass fiber weave as protection to work on. The first idea for a covering was a prefabricated stretched membrane made of glass fiber weave coated Teflon. This membrane was to be sealed with 20 mm wide overlapping seals every 1.000 mm, but could be made completely prefabricated. But the architect did not like the idea of the seams of 2mm thickness. The second prototype mock-up took again the same steel substructure with aluminium battens and covered with 2 layers of foam panels: one screwed and the top layer glued onto the lower foam layer, provided with a harder top surface to work on. On top of the upper foam layer a 20 mm thick layer of prefabricated granulate rubber was glued, covered with a thick yoghurt-like gelcoat layer. This ensemble was to be made on site in its entirety. The only prefabricated components were the composite noses, that could be bent and twisted on site before applying the rubber layer. This was a solution to which the architect did not object. However, when he saw the composite sandwich shell prototype, which had been produced in parallel, he was flabbergasted with the composite sandwich concept. Plan A became Plan AA. So a second sandwich prototype mock-up was made with a different nose in the factory of Holland Composites [Fig.41].



FIG. 38 First Plan B prototype with a stressed membrane on top of 2 layers of foam on a tubular structure



FIG. 39 Second Plan B prototype in a steel and aluminum construction locally produced with prefab GRP noses

The three 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 in a dramatic reduction of the cost price, as we were more and more familiar with the experimental aspects and how to resolve these. Making more prototypes with our hands on approach with the various materials, made cold feet, if any, disappear. In the factory, where the partial wing segments were at easy workable heights, the high latitude of working on the roofs had not been considered, nor did the architect take that this in consideration for the viewing and judging distance of the finalized product. The roofs had to be installed at

a height of ~40m and without a proper scaffolding to work from. This is, by the way, the reason that my students at the Faculty of Architecture already for 20 years learn to make their own prototypes. These are based on their designs and made with their own two hands in small groups inside the TU Delft prototype laboratory, which is basically a mini-Octatube laboratory. After 20 years more than 1.000 students have enjoyed this opportunity as part of one of their study modules. A number of these students have said “after making prototypes of our own designs we see the light in our architecture study”. It accelerated their thinking, as it did ours in our prototype contract for this project as well as others.

[ref. Mick Eekhout, Peter van Swieten: 'The Prototype Laboratory', IOS 2015, ISBN 9781614995456]



FIG. 40 Third and preferred Plan AA prototype with a completely prefabricated sandwich construction with parallel top and bottom



FIG. 41 Part of a single mock-up of the vacuum injection method with a thin skin and a flat surface to check the sandwich composition and the nose form, as a variation of the third prototype

DESIGN DEVELOPMENT OF THE MAIN FEATURES

A few months followed with design contemplations, during which time, initially from the side of Mick Eekhout and later on from Sieb Wichers, 43 letters were addressed to Moshe Safdie, who promptly responded to primary design considerations at hand. The answers came by mail and by telephone as the fountain pen magically covers distances between designers [fig. 42]. In much the same way the arguments on production level were laid down in a correspondence between Sieb Wichers and Holland Composites. The route from redesign and pre-engineering to final design took one full year involving sometimes, but not continuously, 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. It was agreed that, in contrast with previous projects involving free form structures at Octatube, there would only be one party involved with computer work. In case of the Municipal Pavilion at the Floriade [Asymptote Architects] the virtual collections of drawings [in a digital office] was not a success as the design development process was too speedy and nobody had much communication experience or skills. The best drawings were made by the architects when the pavilion was already opened. In this case the Octatube engineering department was in the lead and the architect could only supervise and give instructions as a guest behind the project designer's monitor of Octatube.

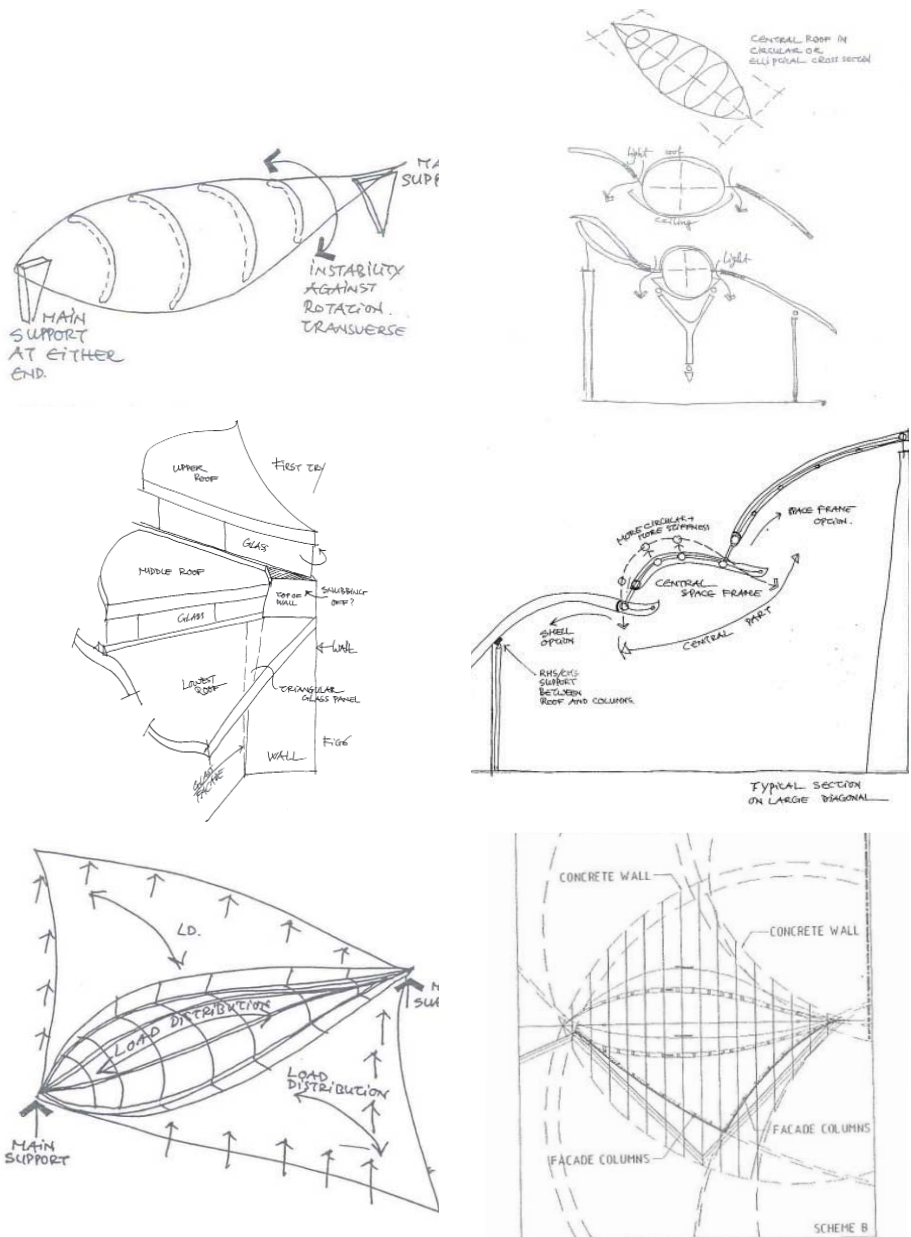
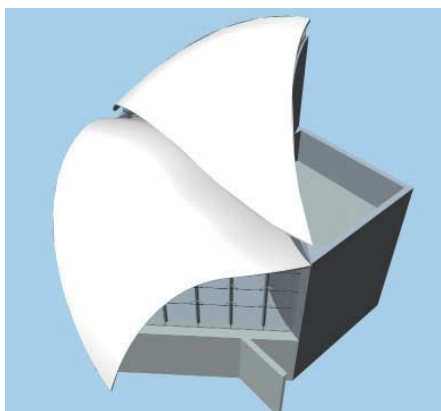


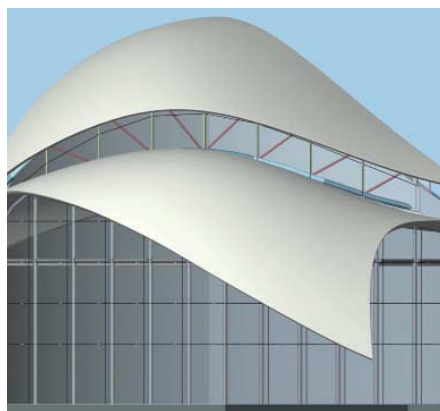
FIG. 42 A number of sketches by Mick Eekhout from this design phase sent directly to Moshe Safdie

FREE FORM ENGINEERING

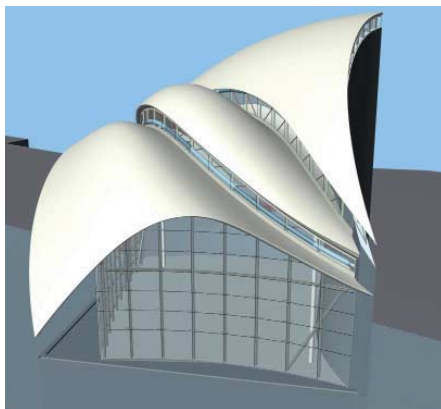
This phase contained a new round of all related aspects in the design development including static analysis, free form design and engineering of the wings including the reinforcements in the sandwich, the production method of vacuum injection of the GRP wings, and all other aspects important for a good overall integration of design and engineering. The Design & Build attitude places all such activities in the hand of one responsible 'Design & Build' party. All problems have to be thought out in principle at the start of the engineering and are developed to workable solutions over the course of the project's development, during which the client had to be patient and not micro manage the process too much. Our experience in the Middle East where 'time and money' are of the essence is that innovation embedded in a time-consuming operation method, is not at all possible. Chasing time and money often has innovative quality as its sacrifice. The pre-engineering and prototype pre-phase took one full year.



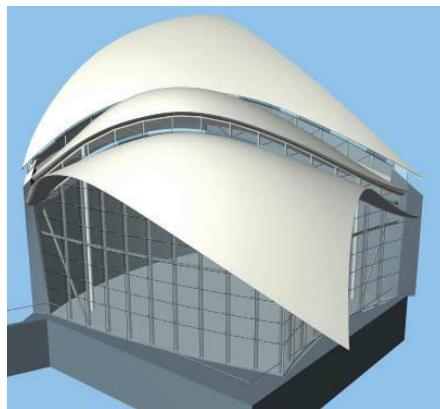
1



2



3



4

FIG. 43 Birdseye and frontal views of 'The Library' and 'The Great Hall' below

Parallel to the prototype development and the redesign principles, Sieb Wichers, a freshly graduated building technical engineer from TU Delft with much experience in free form technology, worked on the free form engineering, to get a grip on that new field of expertise. This engineering development started on the basis of AutoCAD and Mechanical Desk Top [fig. 43].

At this stage, Octatube acted rather innocent towards possible consequences of dealing with the responsibilities of a complete redesign of the free-form roofs, due to unfamiliarity with digital control on free-form design, one of the major innovations in this project. Fed by the then recent developments in education of young students as the upcoming talent at the university, Octatube dared to take the responsibility of such a redesign. Having the full responsibility of the entire project in the hand of one person is in fact, quite risky. In this case the engineer Sieb Wichers did not only do this redesign and the engineering, but would later in the process also become responsible for the realization on-site as the project leader of Octatube. Although he never took any sick or emergency leave, in hindsight it would have been wise to have at least two responsible people on such a job and in such an important role to ensure the project's continuity.

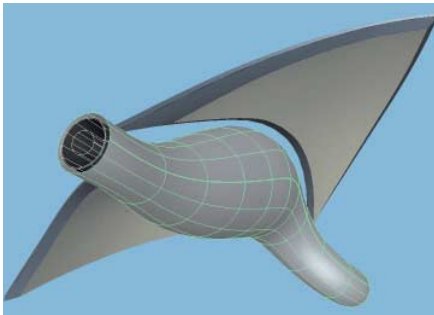


FIG. 44 Design body

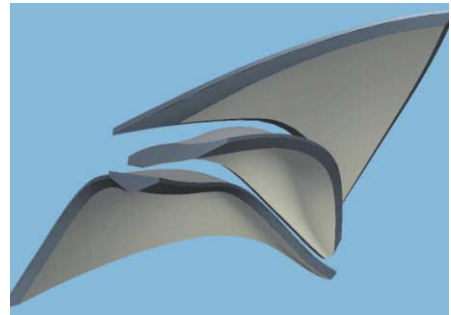


FIG. 45 Plane design

Architectural and building technical engineers educated at the TU Delft are elaborately trained using Maya and other 3D-software programs. Students are both skilled in architectural design and in building technical engineering. They are able to design and engineer free form architectural compositions. In the Chair of Product Development at the TU Delft, a research group 'Free Form Technology' was active from 2002 up to 2009. This led to a book 'Free Form Technology from Delft' [Ref. Mick eekhout et al, 'Free Form Designs from Delft', IOS 2015]. One of the colleague part-time professors, Kas Oosterhuis had an independent and successful group of staff and students on 'Hyperbody' (www.hyperbody.nl), more focused on interactivity and short routes 'From File to Factory' for the making of elements and components of his free form buildings, which he calls 'non-standard' architecture.



FIG. 46 Cover 'Free Form Technology'

The glass bay windows of the Rabin Center, which visually separate and structurally connect the shells, were initially thought to be twisted and therefore cold bend on-site. This technique was already a proven skill within Octatube's crafts, even for double glazing, since the cold twisting application of double glass units $1 \times 2 \text{ m}^2$ for the town hall of Alphen aan den Rijn, as designed by Erick van Egeraat. These panels were twisted 50 mm out of its plane in 2003. Dries Staaks, a graduate student from Eindhoven University, would compose his graduation work the '*Cold Twisting of Glass, The Theory of Cold Twisting of Glass panels by Dries Staaks*', 2004 Octatube, Delft, on the cold twisting of glass panels at Octatube in 2004 [fig. 47, 48]. This project is reported in chapter 13 of the book 'Lectures on Innovation in Building Technology' by Mick Eekhout.

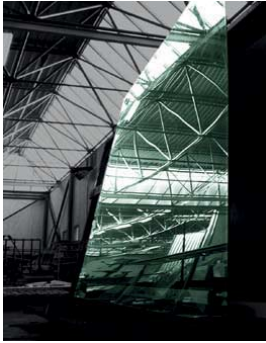


FIG. 47 Cold twisted glass panel in factory of Octatube

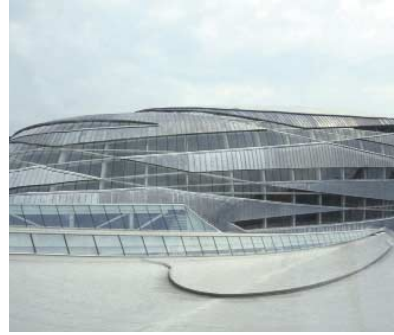


FIG. 48 Back side of the town hall of Alphen aan den Rijn

STRUCTURAL BEHAVIOUR OF THE SANDWICH CONSTRUCTION

As we started with the surfboard principle, it was originally thought that the wing structures would obtain their strength from the two polyester reinforced skins separated by a lightweight 300 mm thick foam core together with the natural stiffness of its doubly curved shape. It was even thought that the core material itself would be milled in shape and glued together into parts roughly the size of 1/3 of one roof and subsequently to laminate the GRP skins on both sides of the core to obtain a surfboard-like structural sandwich. Later on this idea was replaced by a vacuum injection mould system as proposed by Holland Composites, where both top and bottom layers were integrally produced, including the foam core interlayer with its reinforcements. Local steel inserts, connected to internal GRP bulkheads and accessible from both sides, would be required for hoisting, mounting and transferring of acting load cases. In a later phase, Solico introduced vertical stringers / shear webs between upper and lower skin at 500mm spacing to enhance the permanent shear resistance of the sandwich. From then on the foam core merely became a mould filling [fig. 49].

At this time the idea to transport the entire wings to Israel was already forgotten: too expensive. We had to decompose each wing into a number of different segments, which were to be produced on individual moulds, shipped over, assembled on site, structurally connected and finished. As designers we had the idea that the shell segments would be transported to the site, carefully positioned and mounted structurally together by bolting or screwing. The tolerances between the individual segments were important, but also the tolerances of each entire wing, as the support points were fixed on the theoretical drawings and visually hidden steel inserts were embedded within each shell segment during vacuum injection. Tolerances were required in each stage of production, such as for the steel jig for the installation of the individual segments, the assembly of the entire wing, the positioning of the columns and the location of their pre-cast anchors in the concrete on different levels. After the required smoothening of the seams by a filler, a top coat would be applied to improve the already reasonable UV-resistance of the resin and polyester skin. After hoisting and installation of each roof wing on its steel supports, only minor damages required a touch up. That was the general idea.

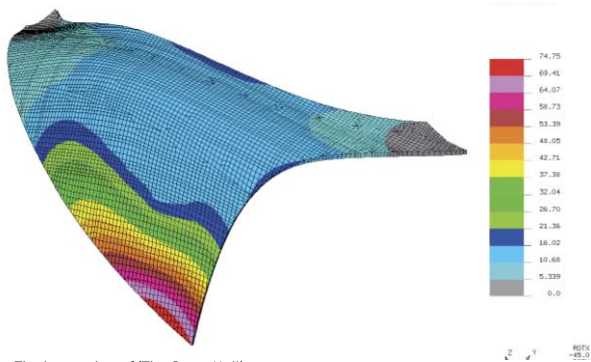
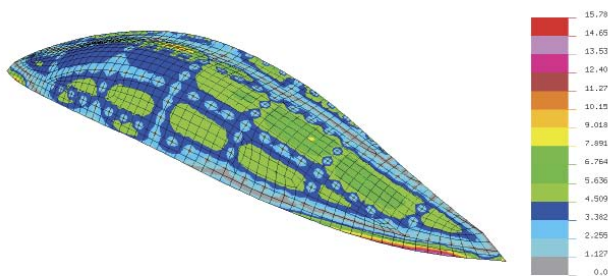
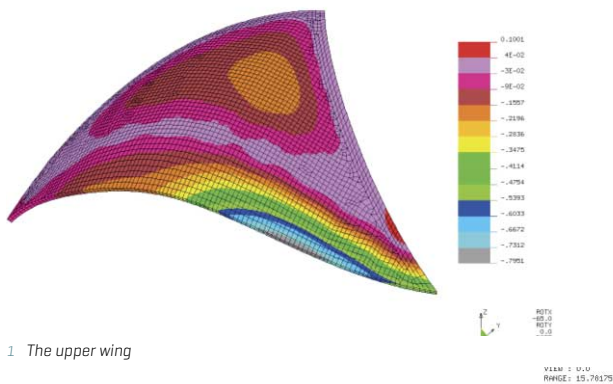


FIG. 49 Structural analysis of deformation of the GRP sandwich roofs made by Solico.

TRIAL ASSEMBLY OF THE FIRST THREE SEGMENTS

It was agreed that the last part of the prototype phase would be the experimental production of 3 of the original segments of the Library [fig. 50]. This way the connection between the segments could be further developed and tested. In addition the overall smoothness could be agreed by the architect, who desired a seamless solution of each wing surface.



FIG. 50 Roof Segments

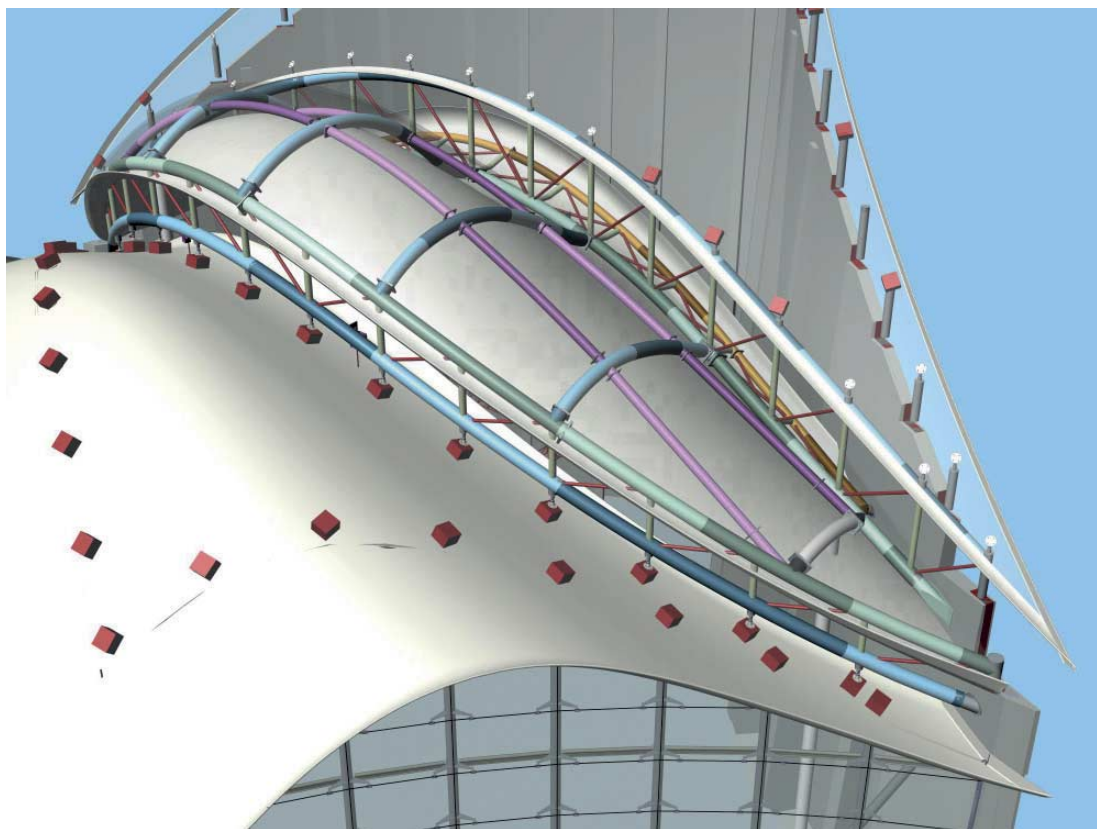


FIG. 51 Fitting of all the roof segments of the lower wing of 'The Library' at Holland Composites

The lessons learned from this prototype were clear. It was decided, due to its relative technical simplicity, that the engineering of the Library had to be done first in a sufficient detailed level, in order to be able to make all necessary fabrication drawings of the 3 segments.

The 3 segments were made according to the vacuum injection method as described in the Production chapter. After production of the first three roof segments of the Library, they were temporarily installed at the premises of Holland Composites as a full-scale mock-up as well as the full size wing later on. The segments were placed on a temporary steel structure in order to fit and align all the segments.

The three segments were connected structurally and the surface was smoothened with the final layers of gel coat in order to prove respectively to the manufacturer HCl, the general contractor Octatube, the architect Safdie and the client Rabin Center, that the wing-shape has the desired fluent shape without any irregularities. This mock-up was built in March while it snowed in Holland. Around that time, we realized that the top height of the Lower Wing of the Great Hall would reach ~11m above floor level when resting on its three wing tips. The consequences of the on-site erection gradually became clear.



04 FINAL ENGINEERING

COMPOSITE SANDWICH SEGMENTS

After approval of the results of the pre-engineering and prototyping phase, the price was agreed for the composite sandwich shells and so the final engineering could commence. This phase contains all thinkable design & engineering aspects that could influence the built result: geometric design and development, static analysis, final production method of vacuum injection of the GFRP wings, assembly connections, fire resistance and logistics in the Netherlands, transport in containers, assembly on the building site, jointing, finishing and finally hoisting the roof shells into position, thus transforming the appearance of the building overnight. The Design & Build attitude places all activities from engineering up to building and finishing in the hand of one responsible party, Octatube in this case. There is no escape; no throwing a problem over the wall to a next party. All problems have to be thought out in principle at the start of the engineering and are developed to workable solutions over the course of this redesign and engineering development, whilst keeping the architect constantly informed.

One of the challenges during the redesign process, was in fact the data transfer between various software programs, which were used by the different disciplines: MAYA v5.0 for basic redesign, RHINOCEROS v3.0 for generation of the basic milling files and translation between several programs, AUTOCAD MECHANICAL DESKTOP v2004 for the basic engineering, shop drawing and 3D analysis and FEMAP v8.0 for the detailed structural analysis of the steel structure and global analysis of the shell structures, were just some of the softwares used. Some of the results are given in fig. 53 and others in this chapter.

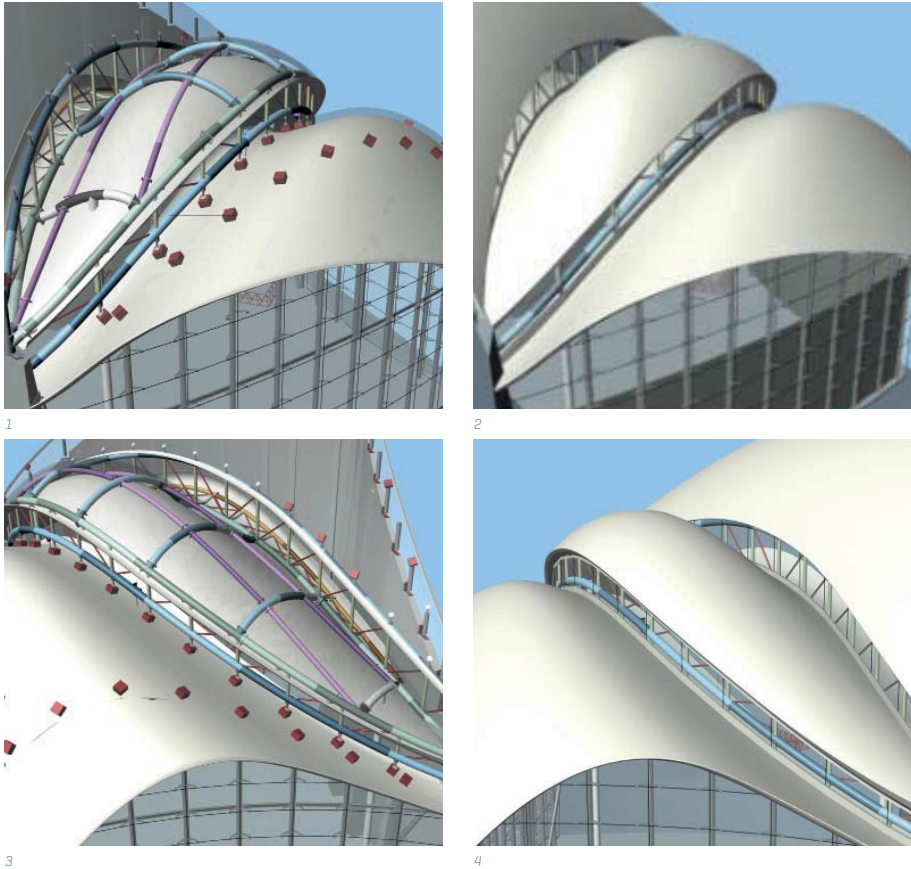


FIG. 52 Engineering model with space frame and inserts and with upper skin, seen from two sides of the Great Hall. All elements and components have to be fixed in their 3D positions in this BIM model 'avant-la-lettre'. Without exact digital positioning this type of free form buildings would not possible to be made in an industrial way

While each of these different softwares were used on their own merits, Octatube had to assure compatibility and accuracy in the data transfer between them all. For example, the structural engineer required the Central Body's wireframe to be split up in shorter pieces, between structural nodes occurring at the nodes of the steel members. Now typically, the software used by the structural engineer can split up these members, but in a very devious manner and only one by one and hence taking hours to execute. To overcome this issue, Rhinoceros was used to do the splits in just one or two clicks prior to sending the resulting [split up] wireframe to the structural engineer. Another example is providing draftsmen with lines normal [perpendicular] to the freeform wing surface to finalize the geometry of the so- called wing connectors. Again a quick operation used in Rhinoceros and results transferred without loss of data straight into Mecanical Desktop for further development. Hence again saving precious time. There are plenty more examples of solutions applied and actions taken in order to overcome compatibility issues between the various programs, but

it is clear that broader solutions must be addressed by software developers and universities in order to create clear “software paths”, which link the computational needs of the various parties involved. While each party should still be using the best suitable software for specific tasks at hand as described in the example above, or Octatube it was an extra degree of innovation, which might be unnecessary in a perfect world, but then again: such challenges arise in any interdisciplinary activity.

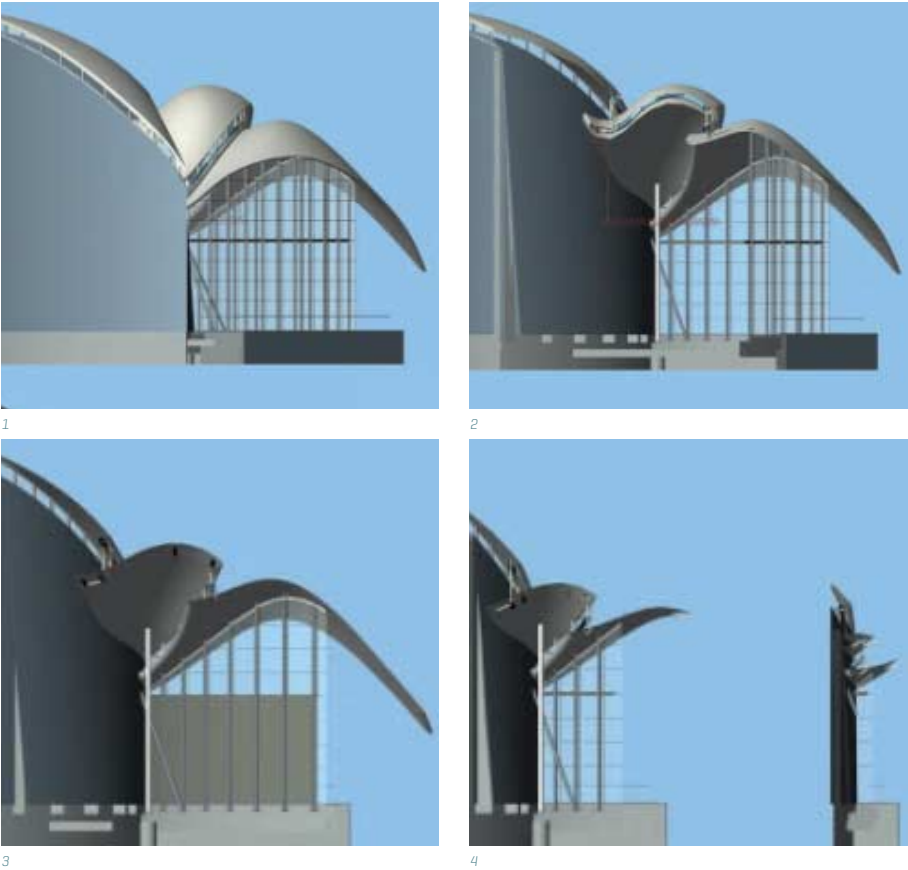


FIG. 53 Close-ups in vertical sections of ‘The Great Hall’ wings with insert points for connectors to connect the wings to the columns and structure of the ‘Central Body’

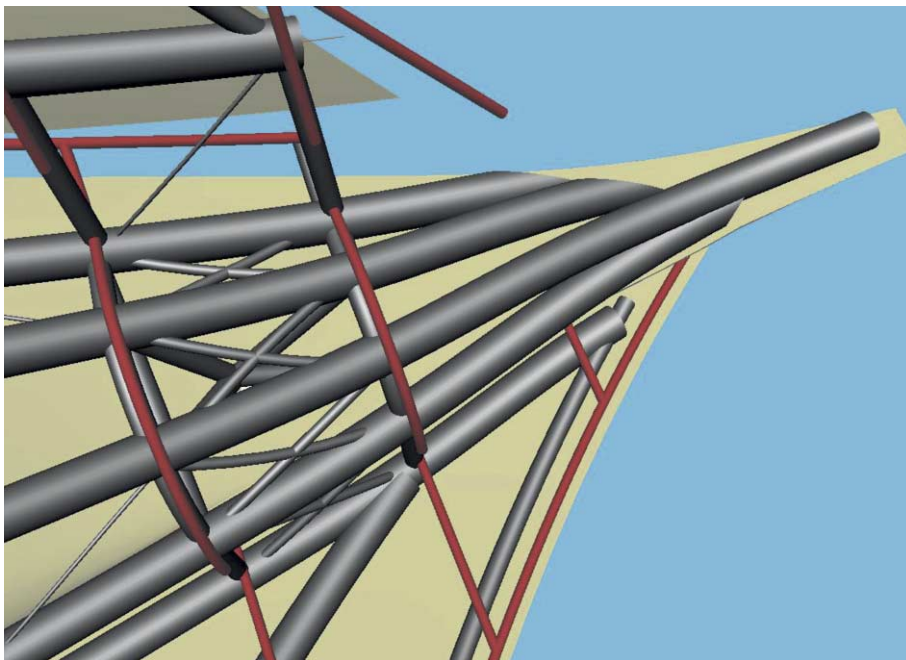
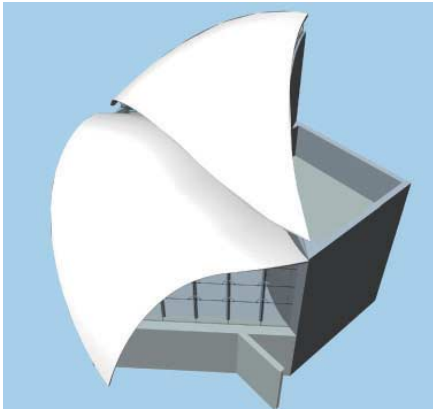


FIG. 54 Tail of the central body in case of the tubular steel structure as the first thoughts of this complex node

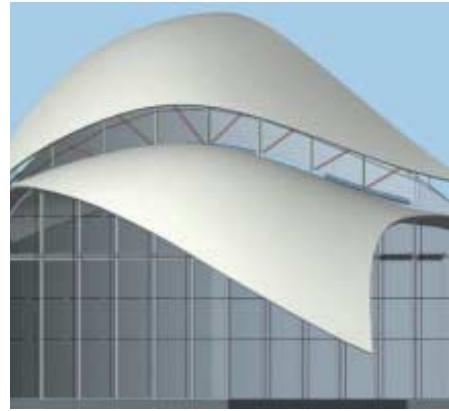
THE LIBRARY FIRST, GREAT HALL AFTER

The final engineering started with the Library, as it was the least complex roof design on all accounts. It was used to familiarize and understand all challenges in order to systematically develop resolutions for each of them. The Library was seen as a 'Zero-series' in production in terms of Mick Eekhout's "Methodology of Product Development in Architecture". The static analysis of the Great Hall however, was far more complex and with greater structural challenges at stake. The roof for this building was therefore done second after the Library.

The definition of the Library wall is geometrically less complex than the Great Hall. An extruded surface from the centerline of the cylindrical wall intersects with a vertical translation of the exterior roof [mould] surface down by 1.300 mm. This intersection is then projected perpendicular [sideways] onto the inner and outer cylindrical surface of the wall. After lofting the new upper edges of these cylindrical surfaces the top of the concrete wall is derived. The cladding of the wall used a same principle, but with a vertical translation of the exterior roof surface by 1.050mm. A cross section radial to the wall now shows two horizontal section lines: one for the cladding top level and one for the concrete top level, which differ 250 mm in height. The above results in a clerestory glass height of about 800 mm from the top of the cladding to the underside of the 200 mm thick Upper Wing.



1



2

FIG. 55 Digital model of the wings of the library

The positions for the façade columns of the Library were already defined 100% by the architect in plan and all that remained was to determine the precast anchors in the floor structure to support them. Also the fairly large distance between the column's centerline and the position of the exterior glass surface of 330 mm was of no further discussion.

The position of the 2D-truss was positioned at 1m North of the building's axis. Hence on top of the concrete wall and no longer located at the exact theoretical transition between the stone clad concrete wall and the glass facades as it would not be able to be anchored in that position, at least not in a way that any designer would appreciate. The position of the truss had influence on the shape and size of the light shelf of the Lower Wing. After discussions with the architect, the final measurement of the cantilevering light shelf was reduced to 750 mm. The glass surface of the bay window was set at 180 mm from steel truss centerline. The upper and lower CHS truss beams were derived by a 3D-offset of 300 mm from the intersection of the vertical steel truss plane with the nearest wing surface. Hence all elements were positioned using parallel distances, a method of approach in the composition of this Library roof in its components. In a later stage, when the wing connector detail was 100% engineered, this 300 mm distance increased to 440 mm to allow for extra vertical tolerances as well as improved feasibility of the connection detail itself, in case of replacement or installation sequence requirements. Hence slightly altering the position of top & bottom truss chords and reducing the active truss height as a result, but within its required structural capacity. This example is to show that nothing can really be finalized if not all related items are turned and that sequence is of great importance in the development of complex free form envelopes [fig. 55].

The next step was the subdivision of the truss verticals. This was a main concern, since the truss was standing on the concrete wall and hence the lower part of the truss would be wrapped inside the cladding and in fact invisible from a position standing on the floor.

The actual subdivision of the truss did not have any consequence for the sandwich panel segmentation. The architect preferred the option with an even subdivision of verticals. The truss height is about 2,5 m in the middle and 1,5 m at each end [fig. 55.2].

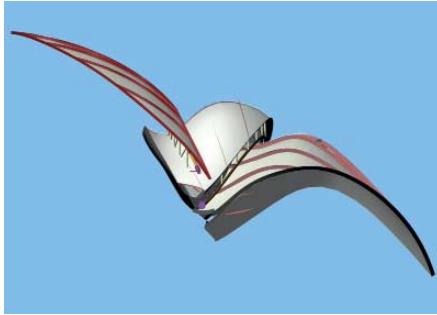


FIG. 56 Wing seams for Great Hall roof shells

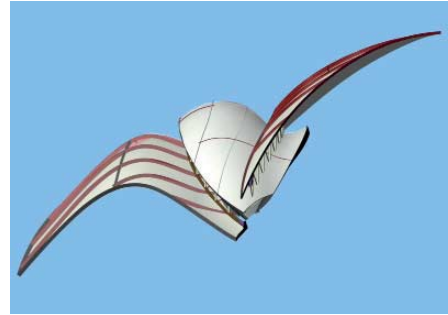


FIG. 57 Wing seams for Great Hall roof shells

The boundaries of both Library wings are determined by trim lines at floor level projected straight up against the mould surface of each wing. Sometimes a flat surface has its virtues as a reference: keep references & setouts straightforward when possible, such that these geometric setout recipes can be handed over to others by following simple steps and always resulting in the same end product.

It was important for the architect to have no direct sunlight in the Library, which caused the extensive cantilevering Upper Wing beyond the steel truss. After all, Moshe Safdie had learned this indirect daylighting from his master Louis Kahn. At this point both wings are thought to be 200 mm thick. In a later stage, the thickness of the Lower Wing increased to 300 mm due to its large cantilevering lower tip. The rounded nose was proposed as a 40mm edge part perpendicular to the mould surface, ending in a 140 mm radius tangentially to the interior wing surface. The architect altered this into an increased radius [1,5x thickness wing] of R=300 mm & R=450 mm for respectively the Upper & Lower Wings combined with the smallest possible [25mm] radius required for production, which was the executed solution. This design was made into 1:1 full-scale models and applying the actual material and was used for review by and approval of the architect.

GRP structural engineer Solico analysed the wings more in detail and developed the construction. They discovered that the main structural loading on the roof was the thermal loading by the sun, causing the upper skin to become stressed under compression, are of its consequences would be that, because of the high thermal insulation of the foam the solar energy would remain entirely in the upper skin which would eliminate from the foam. To restore the structural sandwich action seringes were introduced, the connections between upper and lower skin [fig. 56 - 63].

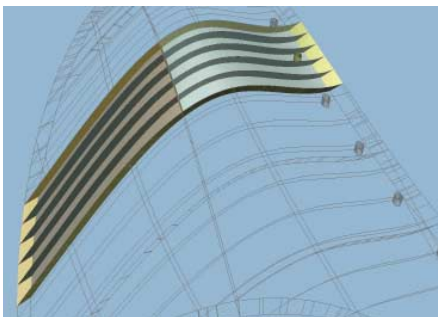


FIG. 58 Stringers in position

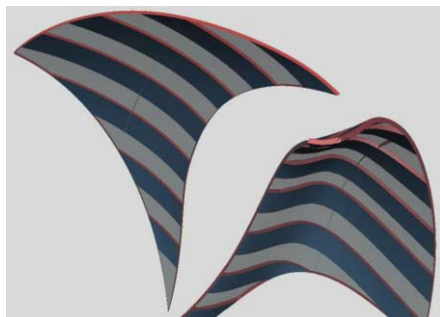


FIG. 59 Wings with segments

At this point of engineering development, the geometry of both wings and their interfaces with the stone clad walls could be finalized. The challenge was to end the tip of the lower wing, the top of the square wall, the foot of the steel truss and the starting point of the cylindrical wall come together in a 'single 3D node' [fig. 54]. The designed height of the square wall determined the level for this node. After the engineering basics had been defined for the Library, they could serve as a starting point for the Great Hall.

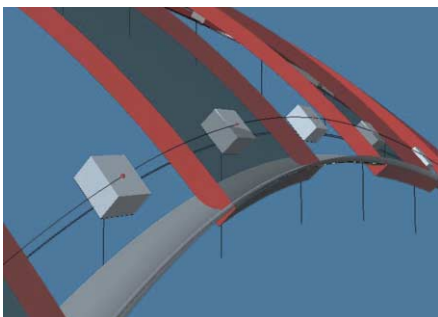


FIG. 60 Schematic wing inserts for connection with columns



FIG. 61 Cast-in steel reinforcement with glass fiber flanges

THE SUBDIVISION OF SEGMENTS AND INSERTS

Investigations were done on the means of transportation. Containerized shipment had influence on the design of the segments, a remarkable issue. The principle idea is to minimize the amount of seams to be finished on the site. The initially chosen means of transportation was by regular 40ft closed containers, with net measures of 12030 x 2335 x 2270 mm. In top view a maximum 2,2 m wide grid (which was later optimized to 3,5 m) was projected vertically onto the mould side of the two structural wings of the Great Hall. The resulting projection lines were then projected onto the interior surface of the wing. After lofting both of these lines, the somewhat twisted seams were created, oriented

continuously perpendicular between inner & outer wing surface. Some segments of both wings exceeded either the 12 m long and or the 1,5 m height restriction of the milling boundary and required an extra division in cross section. In the 3D-model, a zone was determined for the possible location of this additional assembly subdivision. The entire Upper Wing of the Great Hall divided into 17 slices would fit in three 40ft containers. The Lower Wing of the Great Hall required a subdivision of 25 segments.

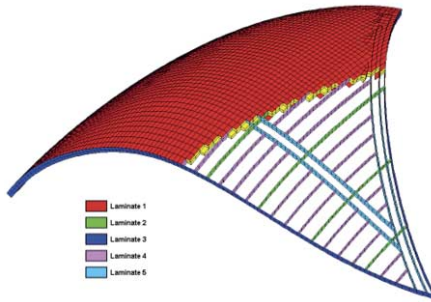


FIG. 62 Original buildup of glass-fiber reinforcements



FIG. 63 Insulation foam and glass-fiber reinforcement

Design and engineering considerations were exchanged between Octatube and HCI. The size for the steel box inserts were finalized to 320 x 320 x 150 mm and analyzed in relation to the most extreme situations, where the box might clash to either the edge / nose or internal hidden seams of a wing [fig. 61]. At this stage, the noses were changed and now to be seen as additional non-structural components laminated on-site to the structural part of the wing. As a consequence, the nosing was no longer required in the milling files of the wing's segments and therefore simplified the moulds somewhat. This was especially the case for both Upper Wings as this change resulted in extra restrictive boundaries for the steel inserts. Besides that, all panels received a recess all around their perimeter to accommodate the 'pre-preg' (prefabricated impregnated glass fiber) connection panels on site to minimize the labor intense hand layup method where possible. A query was raised whether or not an insert could be located in the recess zone. The answer was: "Yes!" The composite engineer Solico determined a minimal distance for the steel insert to the center of a seam to be $7+25 = 32$ mm. This optimistic answer, however, complicated the detailing even more. The rising parts of the Upper Wings above the walls limited the dimensions of the insert, as it rotates towards the panel seam with its upper corner, as one side had to run parallel to the wings edge in order to fit. The 3D-model in the MAYA-program was expanded with the true location and shape of the twisted theoretical seams as well as the required orientation of the steel inserts to anticipate possible clashes. Wherever a clash occurred, either the seam was moved slightly or if no other option available, the insert's corner was chamfered, which eventually only occurred for a handful of them. This would have no impact on the tolerances required for the connection to the column's wing connector as the difference between the circular plate of this connection

and the square geometry of the box would never really be utilized. Chamfering of these steel inserts simply created more types as well as complicated their fabrication somewhat.

At this stage the connection of the steel columns to the wing surface was determined only as a hinge point and initially visualized as a spherical component half submerged in the surface of the wing, the structural engineer's theoretically preferred location. The spherical detail, besides hinging, conceptually showed the requirement for the many angles it would have to cope with as a result of the free form wing surface in different slopes and the vertical position of the column.

WATER MANAGEMENT

The water management at the upper side of the designed wings at the so-called '3D-corners' was quite difficult and up to this day still is. To reduce some of the difficulties, the design made the ending of the wings about 100 mm lower than the level of the stone clad wall. At this very point the wings, the glass strip, the concrete wall and the cladding had to be composed in space. This was not an easy task to say the least. Actually normally it would be the architect's task. However, this task can only be performed when the architect would be in charge of the BIM engineering. Our fingers were not long enough; we had no say in the stonework. The best design solution would have been if the concrete wall had a cut out space to end both wings and glass strip. Alas the concrete walls have not been finished with stone cladding at present day, so the corners miss their finishing all together.

For the architect as well as for the structural and construction engineers, it was interesting to review the shape of the wing piercing into the 80mm shallow depth of cladding on the wall. On the West side, where the wing grabs around the corner of the wall edge, the trim line of the light shelf was positioned in such a way, that the length of the wing on each side of the vertical wall edge would be more or less the same. This allowed for descent and similar hidden connections on each side of this corner. On the East side, it was the goal to reduce the length of the wing connection to the wall. The vertical shape of both Lower Wing's tips were also adapted for proper outward water drainage. Without this adaptation, a shallow pool of water of about 1m² and 200mm deep would occur. Optimizing the above, the starting points were unchanged: the lower tubular beam of the truss would stay out of sight for the people standing below as well as the uprights on top of the light shelf, which light the Upper Wing. Besides this, in front view and in other views, the contour lines of the wings, the truss and the walls all had to be in harmony. Main question raised by Octatube: where does the water run, after it leaves the wing? The absence of edge ribs lets water and filth drain over the roof edges uncontrollably. Especially after the dry season, when desert dust has collected on the roof for months in row and the first rain is falling, dark red or brownish stripes would become visual and spoil the clean white surface of the roof edges. This question was never answered only until after erection of the roofs. It was only 4 years after completion that attempts were made to add a profile to the roof edge, but these solutions were vetoed away by the architect. Cleaning regularly would be necessary as a part of the solution to keep the surface of the wings clean. The realised built wings had to resemble as abstract as possible, in fact resemble the engineering drawing [fig. 64].

On top of both Lower Wings and the Central Body, the water flows from the respective local high points towards the lower areas along the bay windows, located vertically between the wings. From there, the water flow was redirected towards the outer wing tips at the connections to the wall. A waterproof plywood ridge below the bay window was positioned on top of the upper skin of the wing to act as a water barrier. Its initial height was set to $\pm 200\text{mm}$ and the thickness following the width of the above positioned U-profile. The detail on top of the plywood was quite fragile in case of water pressure. A computer model was created to predict the flow of rain water, running perpendicular to the height lines of the upper wings surfaces generated in this model. Besides this study, 1:50 scale models were made of each roof wing to get accustomed to the form of the roofs in the prototype phase. These models came in handy as the manipulation of such scale models stimulated the imagination and engineering steps to be taken.

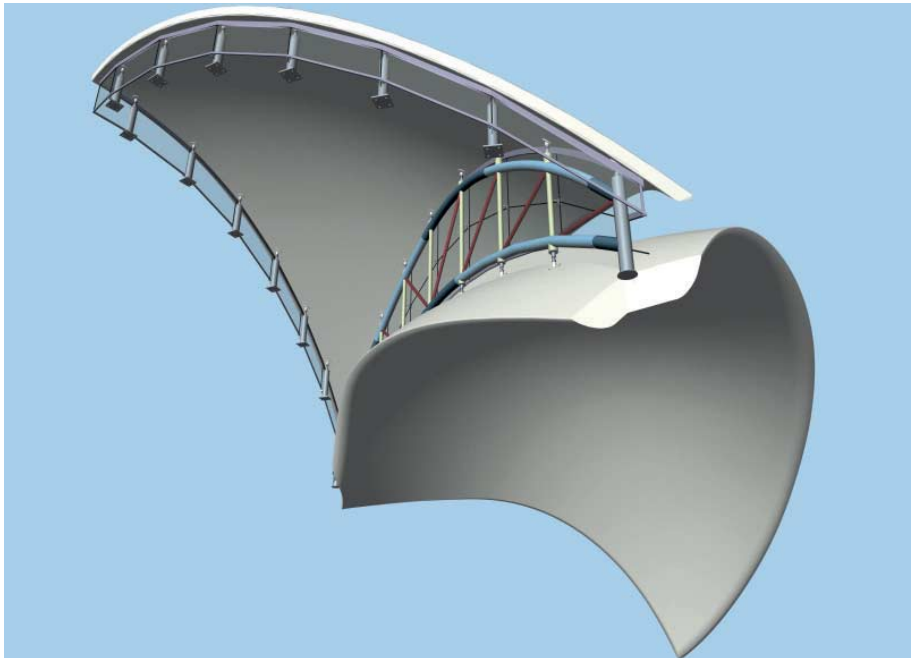


FIG. 64 View of Library wings with truss

In this stage, all noses were rounded off and structural like the rest of the wing. The connection of the clerestory above the wall to the underside of the wing ran right next to the tangent line of the rounded nose. However with the new architectural concept of a bigger radius as mentioned before, the glass would connect to the nose. Therefore the architect proposed to reposition the columns inwards, a-centric on the wall. In the Library, the structural engineers found a structural solution for this offset, due to the big width of

the wall (350 mm), but in the Great Hall, it would be no option for the (200 mm wide) tall wall, which in fact was too slender to begin with. As a result it was decided for the Upper Wing edges of both buildings, to change the rounded nose to a vertical flat edge, cut perfectly in line with the concrete wall's outer cladding surface.

FIRE RESISTANCE

In the mean time, the project supervisors asked for the fire resistance properties of the roof system. The new high-end roofs required to be certified for abundant fire resistance. No escape as the original roof was to be executed in reinforced concrete. Data collecting of all materials started, split-up into resin for the exterior skin, foam + resin for the core and resin & finishing for the interior skin. In general, the resins were already tested and are self-extinguishable according to British Standard.

A fire resistance test at the official Dutch institute TNO was prepared and executed within two weeks. The report and another test sample for the Israeli Institute were sent out. To improve the fire resistance, Octatube proposed to apply a plaster on the ceiling, with satisfactory properties for fire-retardency.



FIG. 65 Standard fireloading on GRP panel



FIG. 66 Wind testing on wind model



FIG. 67 Wind testing on wind model

Wind tunnel tests were mandatory to ascertain the wind pressures and suctions on the roofs [fig. 66, 67]. The building is situated on a hillside with upward and turbulent wind loads, resulting in upward loadings on the wing shells. The results of these wind tunnel tests were incorporated in the static analysis of the GFRP sandwich shells by Solico.

STEEL STRUCTURE

During the pre-engineering and prototype phase, the final choice of the architect based on provided prototypes and studies executed, was the integral GFRP sandwich structure, as we anticipated. Each sandwich shell roof would be without any steel structure, leaving merely elliptical [later on circular] steel columns to support the glass façades and roof shells and to transfer these dead loads combined with life loads to the underlying concrete floor & wall structures. The visible steel components would be hot-dip galvanized and powder coated. Only locally, they would be protected against fire by utilizing a fire in-tumescent paint system and even filling them with concrete to achieve required fire rating and to prevent their premature failure due to fire.

The stepped anchoring for the short columns on top of the walls, was quite difficult to build, at least more challenging than the Israeli contractors could handle, due to the complexity of the cylindrical concrete back walls and the required tolerances for the connections between the steel columns and the GFRP wings.

Octatube had no choice but to design, engineer and visually inspect the stepping concrete walls themselves as well, including the setting out of the anchors and checking of the anchor positions after pouring of the concrete as the Israeli contractor was not equipped to execute this task. In order to support all cast-in anchors in the concrete walls, Octatube was asked to provide a placement plan and anchor specifications including all 3D-coordinates. The main contractor would purchase the anchors, install them and provide Octatube with a 3D-measure control, as agreed before the concrete was poured.

The pouring of the concrete was done from steel scaffoldings and in different stages due to the height of the walls.



FIG. 68 3D-concrete wall poured by the main contractor as which the footplates of the stanchion ends were to be fixed (fig 69.2).

WING CONNECTOR

The connection of the steel columns to the wing was further detailed, but not 100% final. A hidden steel box shaped insert with a 15 mm thick base of 320 x 320 was thought to be included inside the wing. The hinge point connection could not be made inside the wing, due to the required structural continuity of the lower composite skin of the wing. Of course the wing concepts being new, these kind of integrated solutions could not yet be implied in addition to the already complicated time pressured puzzle. This would simply be too complex and risky. Division between wing and steel was set as the thickness of the structural wings were finalized [214 & 314 mm]. Due to the presence of a minimal curvature of the wing and for optimal transfer of forces between the column head and the wing, a 10 mm neoprene disk materialized this separation. A spherical hinge was born and positioned as close as possible to the wing's surface as requested by the structural engineers, to minimize local bending moments in the wing. The required tolerances in vertical direction were not yet known and set to ± 50 mm, which may seem like a lot but the large scale of these roofs, the complexity of the positioning of the steel on the concrete and various other uncertainties could easily request for such large adjustments. This anticipated flexibility increased the complexity of affected details quite a bit. The connector was integrated too much with the column and its central core consisted of too many parts. Besides that, it was not yet demountable after installation of the wings. Hence as a result on-site drilling would not be feasible nor its replacement should it be necessary. Further optimization was required for this complex puzzle, but the first steps were taken.

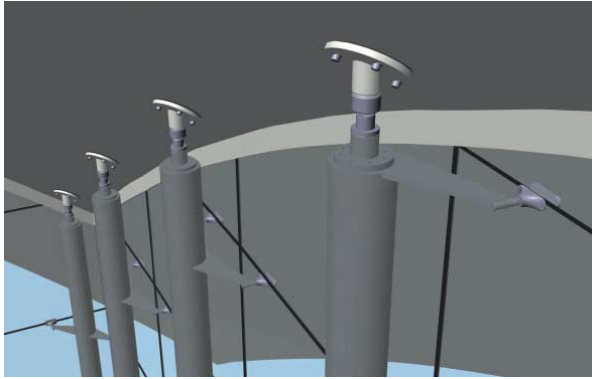


FIG. 69 Ball joint upper parts of the columns in the Library, the ball hidden in the upper cylindrical parts

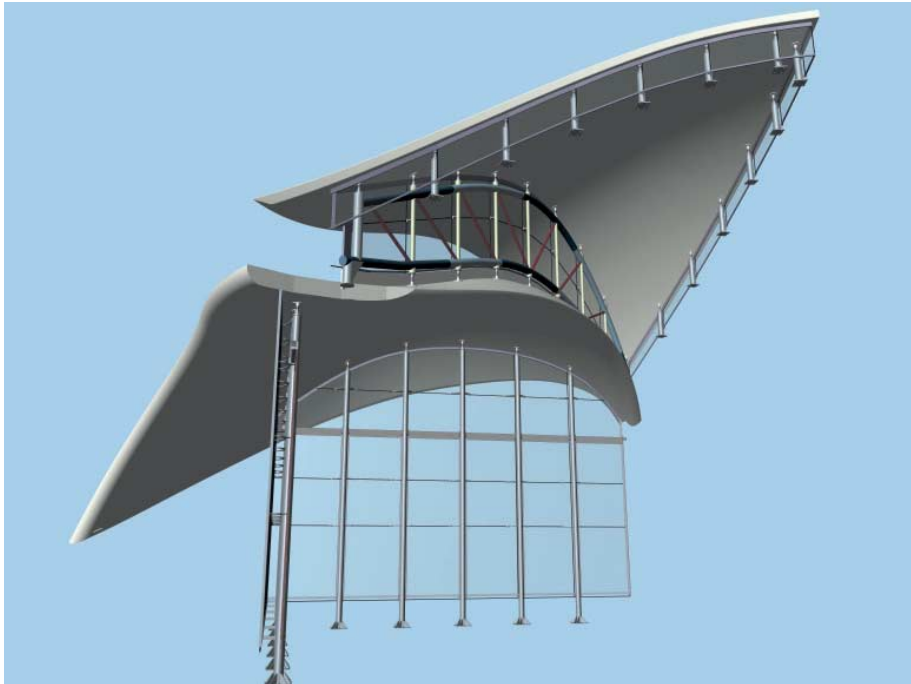


FIG. 70 Ball joint upper parts of the columns in the Library, the ball hidden in the upper cylindrical parts

The final solution for the wing connector was found in three sizes, based on M45, M52 & M56 threaded bar and related spherical hinge sizes. The tolerance in Z-direction was reduced to only ± 25 mm. If really required later on, additional vertical tolerance could come from the anchors at the base plate of the steel columns. Octatube became more and more confident that this would not be necessary, since the wing would then likely appear 'wavy',

thus unacceptable to all parties. All proportions fell into place, the structural needs were met, it was completely demountable for on-site drilling and replacement and the colors were determined. Octatube's photo realistic rendering as sent to the architect, would not differ much from the final result. A 1:1 mockup was shown to the architect, who described it as "an amazing piece of engineering". The solution finally completely accepted and therefore ready for immediate production.

Photographs of a prototype wing connector and exploded views into its separate machined components gave a clear clarification to the architect. Each connector consists of six separate parts, two of which are powder coated and the others in stainless steel. The spherical hinge minimizes bending forces in the wing and tolerates a minor degree in variation of the angle due to site conditions. This spherical part is screwed on top of a threaded bar and fixed with loc-tite. The threaded bar goes into the base part (RAL 9002) and is locked with a cylindrical nut. The spherical head can be fixed to the upper part with a counter shaped component. The upper part (RAL 9010) is bolted to the wing, separated by a (2x 5mm) neoprene disc. This disc prevents damage to the (glass fibers of the) surface of the wing, prevents the finishing plaster layer from cracks and deals with local curvatures and inaccuracies of the wing for a better spread of forces. Around the upper part of the connector, an acrylic white silicon will separate steel from plaster and attends to a neat practical and architectural finish.

STEEL STRUCTURE OF THE CENTRAL BODY.

The structural analysis of both Octatube Engineering as well as Solico indicated that a steel space frame in the Central Body was inevitable. Mick Eekhout had already devoted a number of letters to Moshe Safdie on the principles of the static design of the steel structure in the Central Body. Octatube started to consider the division possibilities of the steel structure of the Central Body. Of main concern were the 36 m long truss spanning between the Central Body and the Lower Wing and the delta-truss spanning between the Central Body and the Upper Wing. Both trusses curve in plan view but are oriented vertically. The twists that occurred in the 3D-model of the scanned scale model by the architect were hugely simplified. The beams in the central part of the body were quickly thought of to become demountable, with shim plates for added on-site tolerance. Basically each truss would be build up in 2, 3 or 4 segments. Latter made transportation in 40ft containers possible as well as the rolling of 3D-curved members out of one piece. Based on a transportable volume of 3,0 x 3,5 x 18 m, the separation into 2 halves could be considered, reducing the overall 9.0m height of the Central Body to a more manageable ~3,5 m. Options to separate in 2 or 4 segments made division halfway possible for easy assembly of two halves. In the MAYA-program the containers were schematically represented and maneuvered onto the free form steel framework. Division in 4 segments was preferred, also from handling and fabrication point of views. This thinking was enough for the engineering phase by the construction engineers and went over to the structural engineers of Octatube Engineering to be worked out in their static analysis.

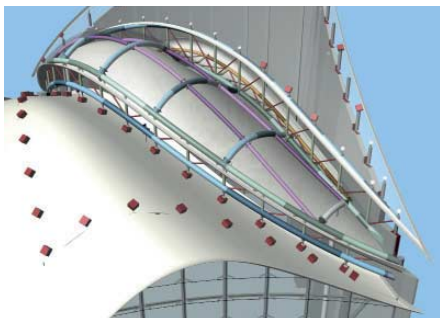


FIG. 71 Internal structural view of the Great Hall wings & body

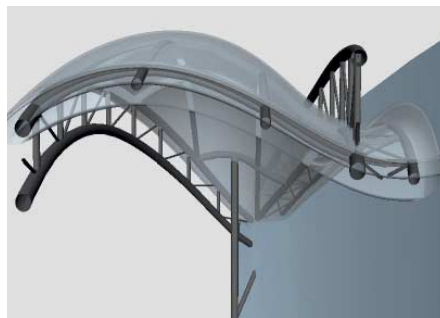


FIG. 72 Section of structural model of the Great Hall body

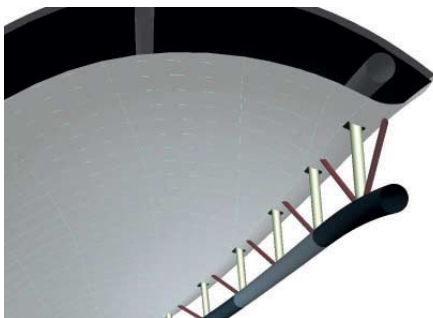


FIG. 73 Section view of Great Hall Lower Wing

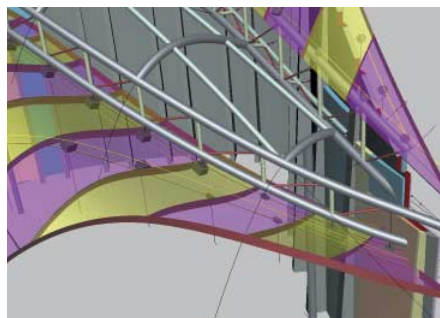


FIG. 74 Segmentation of the Great Hall wings

GLAZING TYPES

Three types of glass facades appeared in the project:

- 1 The glass facades, which are the tall facades below the Lower Wing. Horizontal aluminum transoms combined with vertical silicon seams, later on changed into frameless insulated and screened glass panels;
- 2 The bay windows, which are the small glass facades spanning between two wings. The original twisted form of these as per the architect's model was later on re-engineered to be purely vertical at a constant offset from the steel truss behind;
- 3 The clerestories, which are the small glass lintels spanning between the top of the concrete walls and the Upper Wings in laminated glass in a vertical position.

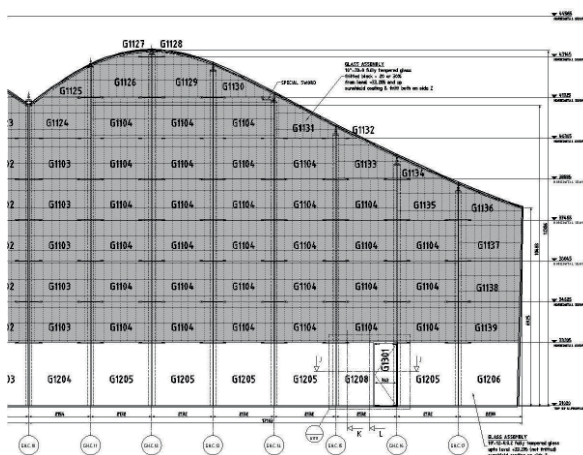


FIG. 75 One of the library facades

GLASS FACADE SYSTEM

Octatube proposed four alternatives for the design of the glass facade system, commonly referred to as 'curtain wall'. This actually is a false name in English as a wall stands on the ground or on a lower structure and a curtain hangs. So we prefer to speak about a glass facade instead. Normally our glass facades are hanging from a structure, located at the top of a building. However, in this case they are standing on the floor structure directly or standing on steel swords welded to the columns. Glass wall? They are all alternatives on the glazing system as specified in the tender documents. All four proposals have vertical silicon seams and therefore only focus on the metal horizontal seams as shown in the specifications.

Proposal 1 following the tender documents with rectangular aluminum profiles and screw and click cap on the outside.

Proposal 2 changed the rectangular into elliptical aluminum profiles on the inside, solely for aesthetical reasons.

Proposal 3 used the elliptical profiles, but exchanged the screw and click cap for local clamping plates and expressed silicon seams. In addition, using tempered glasses double high panels of 1420 mm instead of the prescribed 710 mm vertical modulation were required for this proposal to become economically viable.

Proposal 4 removals of the elliptical girders as well, resulting in a completely frameless glazing system, with point held glass and 14mm wide expressed silicon seams.

The aluminum profiles now fully replaced by steel swords, which were welded to the steel columns. Early on, a vertical rod for carrying the dead loads of the façade was added, leading the forces up to the highest sword, which would have a vertical stiffening plates to address the load case.

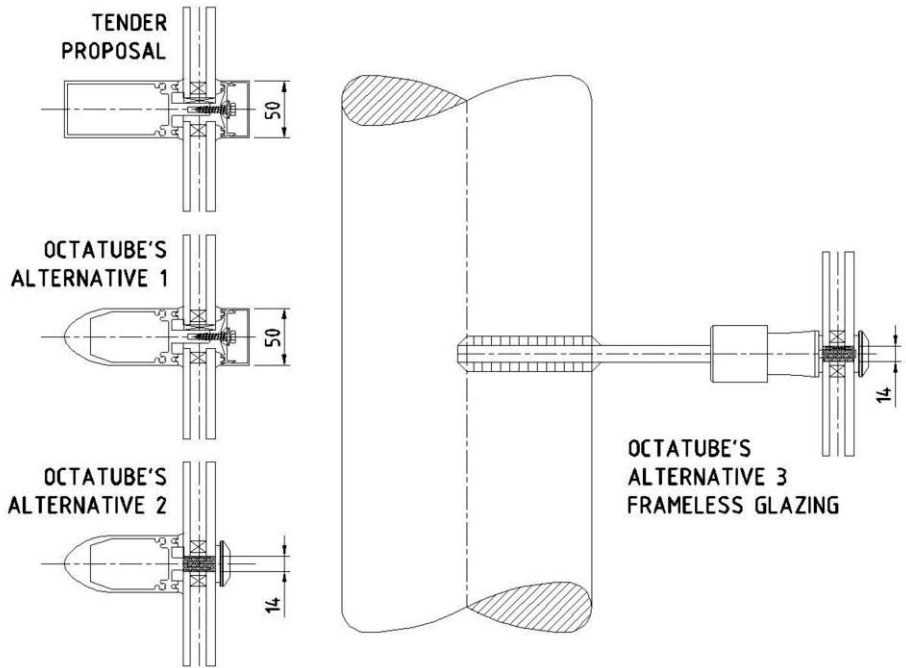


FIG. 76 Several facade detail proposals

The fourth proposal avoids numerous of architectural and detail connection difficulties like the huge horizontal girders running obliquely against the glass to wing interface with cover plates finding little or no support. Without accepting site cutting, the girder endings were not exactly known and would need to align perfectly against the installed position of the roof shell. These endings in some cases would become extremely long and pointy and hence the chances of non-fitting prefabricated girders were not imaginary to say the least. Also, the horizontal transoms would no longer pierce the cladding of the wall at every horizontal seam. Octatube's whole new proposal would result in a very contemporary and transparent formation of image of the glass façade wall in general and could easily compete with the specially designed high-end roof shells. Without doubt, the architect loved the frameless alternative, if it would not inflict with the budget. On its turn and freed from the alignment with the metal panels, the double high glass panels required no further

discussion and were approved as such. Also the fritted alternative of the Library façades instead of rows with aluminum panels for shading appealed to the architect, again only if no impact to budget and schedule.

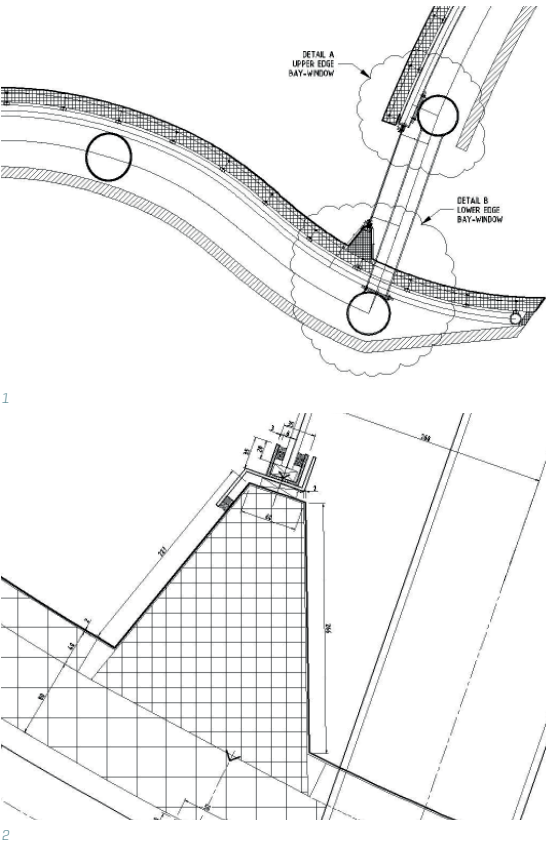


FIG. 77 Detail of glass banana sleeve and lower detail

The tempered glass proposed for the façades was 8-12-5.5.2 for the lowest row and 8-15-6 for all higher rows. In addition to this the question was raised to increase the height from 710 to 1420 mm, omitting the exterior fixation strips and replacing them by silicon seams with local clamping plates as mentioned before. Hence during this phase the overall character of the glass façades changed dramatically.

A discussion arose about the illogical glass specification of green non-tempered annealed glass. This glass absorbs an enormous amount of energy because of its color pigment and would crack as it was only annealed and not pre-stressed. The glass had to be either

tempered or chosen as transparent. Remarks made by the architect concerning the glass type followed the same week. The specifications demanded Viracon VE2-2M, which is a green tinted glass with a soft coating, endorsed by the given technical specifications. The information supplied by Landmann, the cladding advisor of the architect, implied the use of Viracon as well. Hence the green glass was to be fully tempered.

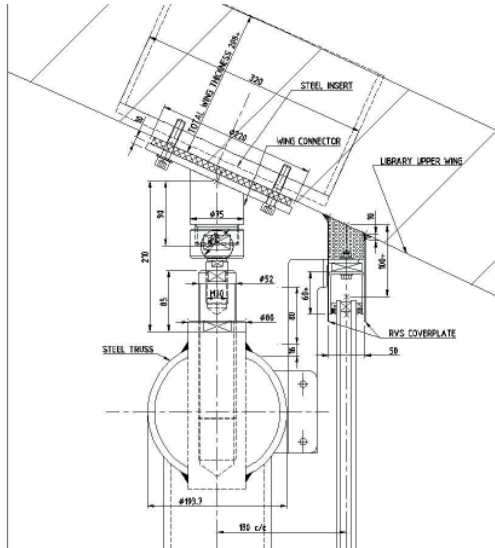


FIG. 78 Upper facade detail

GLASS TO WING CONNECTION

Around that time, the connection detail of the interface between the upper glass line with the wing made its first evolving steps. The basic conceptual idea was to structurally connect to the steel column and creating a flexible watertight connection to the wing, because drilling in the wing was impossible and too complex for the composites co-maker. He would not be able to provide inserts of some kind at the required position with high tolerances during the vacuum injection production. A structural arm would pierce the Connection detail for creation of a hidden bolt connection behind two architectural cover plates. These vertical plates would follow the fluid geometry of the wing with their upper edge, but would be polygonal at the lower side in order to simplify the glass shape. Here again, too many parts, too much detailing. It would become the last detail to be fully solved.

The architect understood the unfeasibility of a non-visible glass connection to the wing. In the original design of the non-structural wings [our plan B, with the steel structure and the thin composite claddings on top and bottom], the glass completely entered the body

of the wings and had no structural implications. At present, this plan B still presents itself in one location along the upper edge of the bay window located on top of the Lower Wing of the Great Hall. Now, the architect demanded that at least the topside of the glass would be curved as to minimize the total height of this detail. This required the lower line of the stainless steel cover plates to then be curved as well. Octatube had a dilemma. Curved glass would increase the price of the glass by 260%, which was no option in this loss-making project. Besides that, the above detailed U-profile would become very complex and expensive as well. The demand for a curvature of the cover plates on both edges was easily granted. Also the bend of the U-profile once at midspan should be no big issue and would already decrease the height of the detail by $\pm 25\%$. Octatube was one step closer to a final detail. The architect kept insisting on minimizing and set the target to Octatube for a maximum acceptable height of ± 100 mm.

ACCEPTATION AND APPROVAL OF DRAWINGS AND STRUCTURAL REPORTS.

The engineering sets of drawings were sent or handed over to the architect on a regular basis. These included drawings from both Octatube and its subcontractors. Octatube enclosed all required overviews, close-up details and wing connector details. From Solico all composite overviews and details were attached and Holland Composites presented a prototype slice of the wing, photographs of the production process and the material samples of safety-eyes to be installed on the roofs for their accessibility during rope access maintenance works. This last idea came from their experiences in yacht building. Explanations were given to the general cladding advisor Landmann.



FIG. 79 Structural testing on panel



FIG. 80 Preparing for perpendicular test

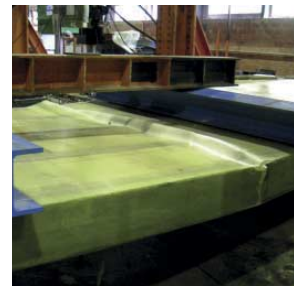


FIG. 81 Material failure during testing

The structural reports on glass and steel for the Library were finished. The report of the Great Hall was still being worked on following the European norms and standards. The deformation of the glass complied with the European norm for frameless glazing [1/100]. The engineering was completely set-up in 3D-models and drawings, which were also used for the structural analysis. Thus the building was engineered as a [BIM: Building Information Model] whole. The geometry was so complex; there was no way around BIM. By developing integral and multi-applicable details throughout the project we had

developed a geometric feasible solution. The advisors had to implement the drawings of different subcontractors, but were at the time generally not experienced in using 3D programs. This slowed down the approval process and led to excuses, which in the future should no longer occur when all related parties can read each other's contributions, while working on the same digital BIM model. Again this project was far ahead of its time.

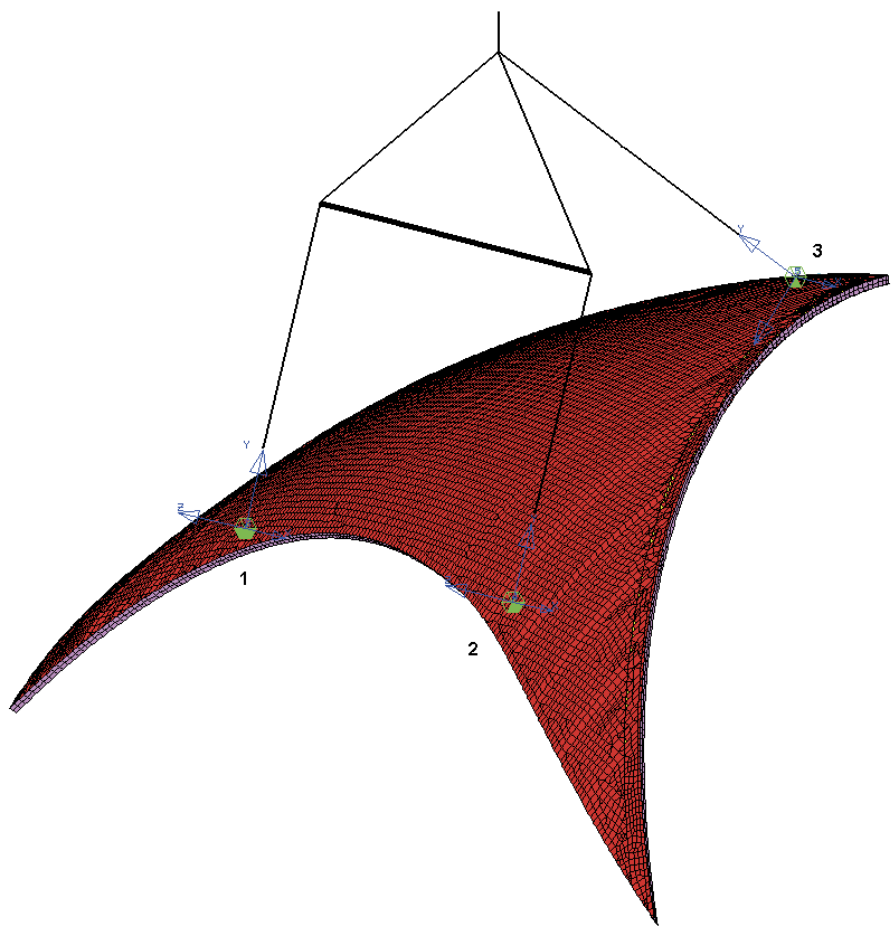


FIG. 82 Hoisting proposals were made for all wings

SUPERVISION BY ADVISORS

At the Israeli side information on allowable composite technology was scarce. Nobody had any experience. No engineer wanted to burn his fingers. An engineering party was contracted from the client's side to approve the work of Octatube. Obtaining the necessary governmental approvals became very complex and due to political change in government from the Labour Party of Rabin to the Likud Party of Sharon, the local government bodies reviewed all proposals with extreme caution. So that many unforeseen and often unnecessary queries were raised by the governmental bodies, which on its turn had to be neutralized by the engineering parties. The impression arose amongst the engineers, that many people in Israel would have liked to see the project uncompleted or stopped half way.

This caution also led to the involvement of the two experts in the field of glass fibre reinforced polyester: two professors of the TU Delft, faculty of Aeronautics, Adriaan Beukers and Michel van Tooren, who had played an unaware role in the Atomium recladding project by their citations [see Chapter 1]. They were invited by the client [The Friends of the Rabin Center] directly to draft a second opinion on the supplied engineering, which was in all regards positive.



05 PRODUCTION

This chapter is mainly filled with the experiences regarding the composite production as an innovation in the building industry as a transfer of technology from the yachting industry with an adaptation for architecture. In January 2005 the go-ahead was given for production. From that time onwards the production of the Library went into operation and the third project year of experimental productions and assemblies started with production of the components on the negative polystyrene moulds. In general, the wiser approach would be to start with the smaller less complicated roof of the Library, although in the back of his mind, the client eventually thought to possibly only build the Great Hall, just in case the costs of the sandwich construction operation would be too high. Regardless of this, the production of the smaller roof of the Library was taken up first. In this book the general knowledge on the GFRP production method is treated without reference to the Library nor the Great Hall, as the production method is the same for both.

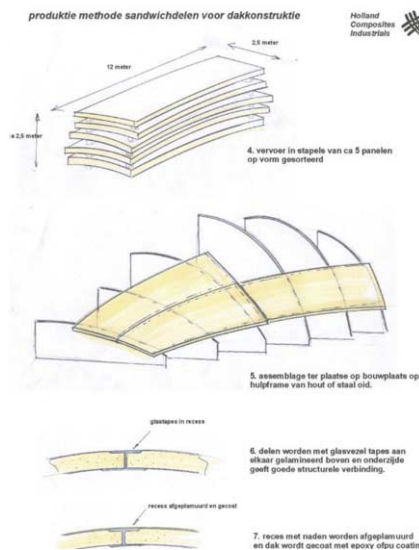


FIG. 83 Initial proposal for timber molds

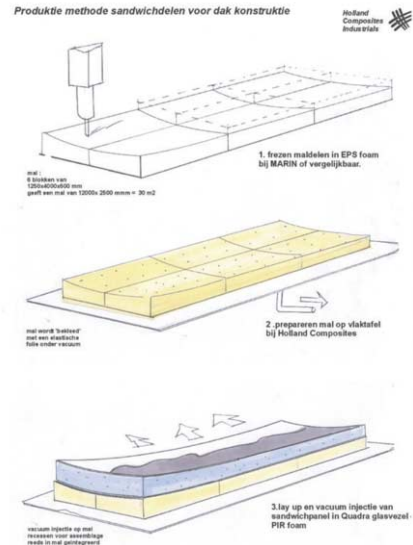


FIG. 84 Later proposal for foam molds

The production technique used in this case has been taken from standard production techniques of producing sailing ship hulls as Holland Composites had produced mono-hull ships with lengths of up to 30 m. Experimental vacuum injected productions meant a clever step, but Holland Composites had never before undertaken such productions for parts with an extreme thickness of 200-300 mm. Experiments and tests would need to be undertaken to ensure their structural integrity. In addition, in case of the sandwich wings the third dimension in the largest wings of 30 x 20m² and the impossibility to sail the wings independent to the site, like a sailing ship is moved over seas, proved to be yet another experimental level for the GFRP production. It was decided that the entire wings would have to be produced in more or less rectangular segments, to ship them stacked in containers and to assemble them on site, connect them structurally and finally hoist them as completely finished wings. That was the outcome of the engineering phase. Hence the segments had to be produced individually in their de-constructed shape of one-off forms. Each segment had a different shape and some were very asymmetrical as well as pointy in nature. The shrinking of these segments during production proved to be an unforeseen adventure. Shrinking of each segment appeared in different directions and during production we wondered how all of these twisted panels could lead to the required smooth wing shape.

DIGITAL PREPARATION PHASE

Considerations were exchanged about possible issues for all relevant parties that might occur during the construction process. These considerations were about milling requirements and boundaries, possibilities within the content of the milling file, transport and rebuilding of mould parts, usage of the mould, orientation of parts, detailing and production of edges, relation between edges and inserts, additional requirements for the actual product and information transfer [points / lines] from mould to product. So the construction engineer had to foresee and to be familiar with the entire process in order to start his engineering. He should be able to undertake the site construction himself, foresee all problems and think of solutions for those eventual problems during engineering. This is very much 'Octatube thinking' and the reasoning behind the Octatube 'Design & Build' approach.



FIG. 85 Panel production photographs

The construction engineer gathered the information and together with the co-makers determined the starting points for optimizing the final wing division into segments. Each milling file of one entire wing made by Sieb Wichers at Octatube contained the boundary box from which the free form body of the wing could be derived. Also included were the 3D-theoretical seams, base points and orientation lines for all inserts, direction lines for bulkheads (as reinforced stringers next to the internal reinforced steel inserts), boundary between interior and exterior of the ceiling (glass lines), coding of panels, 3D-orientated optimized position of the 'milling box' (3,6 x 1,5 x 12 m) per segment, reference cube of 1 x 1 x 1 m and last but not least: 2D-drawings defining the construction concept of the edges. As explained in Chapter 6: Transportations, the width of the segments in the mean time increased from 2.4m to 3.5m in order to reduce overall seam length and on-site labor efforts.

After division of the wing by Octatube, the files were sent to the milling company Marin (now called NedCam in Duiven, NL) for a first control of the optimized bounding boxes of each segment. After approval by Marin, the files were then completed by Octatube using AutoCAD Mechanical Desktop 2004 and exported using the iges-file as a mediator.



FIG. 86 Demolding of GRP segment



FIG. 87 Vacuum resin injection

At the Marin company, every panel of a wing was reduced by 6mm along its boundary. This would create the theoretical seam of $(6+6+1+1=)$ 14 mm, since the mould was finished with a smoothing and hardening layer of ± 1 mm. After these adaptations, the file was send back to Octatube for control. With Octatube's approval in its hand, Marin then took each segment out of its context and computed them into separate milling files. In these files, every shell part was orientated as flat as possible in order to reduce the volume of the mould followed by the milling volume, in order to achieve an acceptable economical cost level for material, milling and transports.

Also the actual composite production was very engineering intensive. A composite factory without an excellent engineering department could not do it. The polystyrene foam blocks for the moulds had been milled accurately by Marin to negative moulds from CAD/CAM files. When the milled moulds arrived at Holland Composites, the surface was first topped with an epoxy skin to work on, and then covered with a plastic foil. In the vacuum-injection procedure glass fiber is impregnated with polyester resin by vacuum suction of the plastic sack around the fibers and foam core blocks and by feeding polyester from the other side to enter into the cavities of the construction: in the fibers and between the blocks. Since the resulting layer of GFRP at the mould side described the desired form of the roof in the best possible way, this side had to become the exterior skin of the roof. From the prototypes it was concluded that the segments had to be produced top-down: the exterior surface needing the most accurate form in the opinion of the architect as the sun would shine over the upper surface and always would result in tangential rays over the surface. Hence revealing any regularity across the roof during certain times of the day.

Less so on the interior side, which is only under influence of the effects of indirect day lighting. So the upper surface had to be made on the mould side and the lower side would have to be made as the top layer and hence a little less accurate and smooth. The fire proofing tests resulted in an extra internal layer of a gypsum-enriched finish, which would heighten the fireproofing characteristic of the inner surface of the wings to the required level. This implicated that large portions of the underside of the segments related to the interior of the building, had to be smoothened after assembly any way.

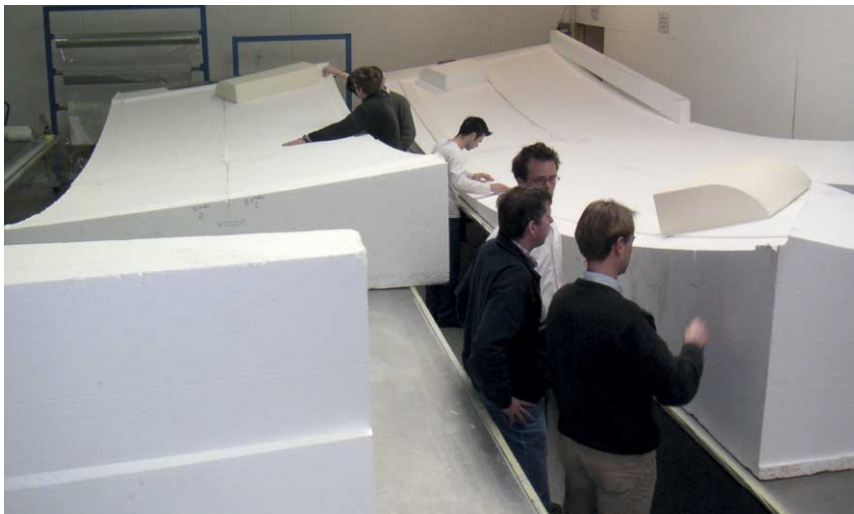


FIG. 88 Check of the machined polystyrene molds

MILLING, TRANSPORT AND ASSEMBLY OF MOULD PARTS

The mould is build up out of separate polystyrene blocks ($H \times W \times L = 1,5 \times 1,2 \times 4,0$ m), resulting in $3 \times 3 = 9$ blocks per mould with a total length of 12 m, a width of 3,6 m and a height of 1,5 m. When the composition of 9 blocks was completed and ready for milling, short lines with a fixed length of 20 cm were drawn across the mutual seams between all polystyrene parts. This appeared to be necessary after the first experiences with the three prototype panels [part of the Library Upper Wing] in order to rebuild the mould at the HCl factory, exactly as it was during milling.

The sum of all required polystyrene volumes approaches ± 940 m³. For comparison, the sum of the net wing volumes is just about 235 m³. So just the moulding alone used almost 4 times the volume of material compared to the end products! About 70% of polystyrene goes to waste during hot-wire cutting and milling! The volume of this waste after milling is tremendous. In comparison, the required polystyrene volume for milling could fill-up 160 containers of 40 ft. Clearly this is ecological not an optimal solution and ready for improvement in a next project. Perhaps when using adjustable 3D-moulds as developed by dr. Karel Vollers, saving on material wastage as well as their transport and handling. Other techniques may then be required for markings and setout information needed in such a scenario.

To reduce cost of milling and minimizing the waste volume, it appeared to be economical to first hot-wire-cut the global shape using another CNC-machine available down the road in Ede. This machine controls each end of the hot-wire in two directions [up/down and forwards/backwards], resulting in nice approximation of the final shape, leaving just a few centimeters for the milling machine, reducing milling time & cost dramatically. This milling machine can both mill and mark with its 5-axis [displacement in X, Y- and Z-direction, rotation around local X- and local Z-axis] CNC-driven milling head. The markings were a perfect outcome and avoided physical ridges or gutters (± 2 mm) in the moulds for recognition of required references. The only ridge remaining was the perimeter edge of the mould of 30mm high.

After milling the surface and edges of the mould were preserved [hardened] and smoothened with a finishing layer of 1 mm translucent epoxy, which allowed all markings to remain visible for further use. Subsequently all mould parts were transported on the road over 90 km from the milling factory in Ede to the composite factory in Lelystad. The transportation and production logistics were organized per wing.

In Lelystad, Holland Composites prepared two completely flat and leveled working floors, on which four moulds could be build-up simultaneously. The HCl team needed about one working day to reconstruct four moulds. The head of production checked the markings and basic dimensions provided by Octatube of each mould before further steps were taken in the vacuum process.

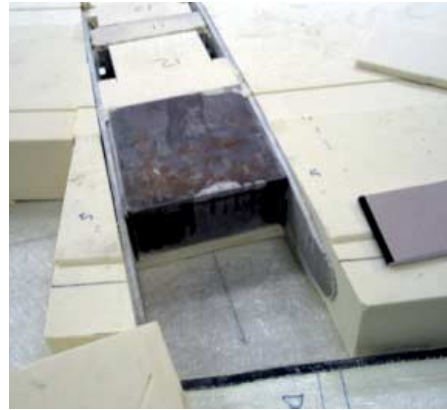
TRANSFER OF TECHNOLOGY OF THE VACUUM INJECTION PROCESS

Step one in the vacuum process, is to copy the mould by creating the first [exterior] skin. When assembled and connected together, along the edges an additional mould part is glued. This part creates the recess required for the structural polyester connection detail between the individual segments applied in a later stage, when all segments are positioned on a large steel pin bed at the building site: the temporary support.

After that, all mould parts were wrapped in a plastic bag with light vacuum suction of $\pm 0,1$ bar to straighten the mould parts as they slightly warped due to the milling process of the polystyrene material. Successively, the lines on the surface of each mould were copied by hand and drawn on the transparent plastic bag in black. On top of this, all glass fiber mats for the outer skin were laid out according to the layout plans made by Solico, the composite engineer. Finally, another bag wrapped these glass fibers. Subsequently, along the edges of the mould many small tubes 10 mm were installed to suck the package vacuum at 3,0 bar. Along the central axis of the mould, three larger 30 mm tubes were installed through which the resin would be injected or better: sucked. The system guaranteed a good and complete flow of resin to all places of the skin as was tested prior during the prototyping phase. Afterwards, when the skin was hardened and the plastic bag was removed, the mould was finally copied with this first skin. This part of copying the mould, took the team also about one working day.



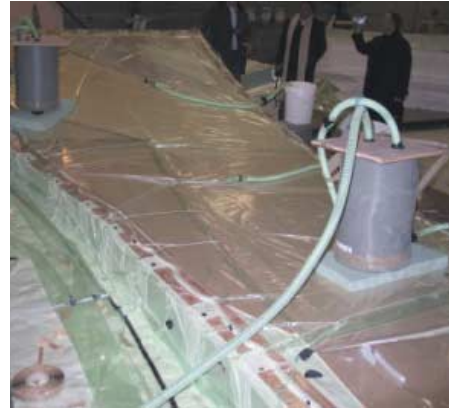
1



2



3



4

FIG. 89 Production of the roof segments at Holland Composites: Vacuum injection of the top layer on foam block milled by Marin. Insert to be placed in the GFRP sandwich roofs in order to make a connection between the roofs and the columns Placement of foam blocks and glass fiber mats, which will become stringers. Vacuum injection of the bottom layer.

Step two in the process, is to prepare all separate parts for the core of the sandwich. It starts with bolting two diamond shaped polyester bulkheads to opposite sides of each insert and fill up the cavities in the inserts with foam in order to prevent them from drowning completely in resin; hence to reduce resin cost and to minimize overall weight of the segments and the wing as a whole. These pre-assembled inserts are then brought into position on the mould, using the base point for position and the connecting line between to base points for direction.

After the top layer of resin soaked fiber was cured, the core of fire-resistant polyisocyanurate [PIR] foam blocks was cut to size and temporary arranged at the correct place in the mould. After finishing the mould puzzle, each strip of foam was taken out. Their long recessed edges were wrapped with 'C'-shaped glass fiber weaves to act as so-called 'stringers' and placed back in the overall puzzle. These stringers would become the structural ribs / shear webs within the sandwich as a replacement of the original steel structure or as stiffening of the sandwich composition, which appeared to have too much flexibility for the roof structure. The foam could possibly delaminate in extreme conditions due to high temperatures of the outer skin in the Israeli sun or due to loading conditions. Note that even after 10 years of solar loading, delamination did not take place, when one hears the sound of the outer surface by knocking with a stick or a hammer. The sound is the same everywhere. Tests and analysis had resulted in the introduction of these stringers to resolve the shear forces in the construction package. The results of the long-term acceleration performance tests, indicated that delamination could occur at the most critical points: at the supports of the columns, between the internal spans and in the cantilevering areas. This is similar to the attachment of an airplane wing to the airplane's fuselage. The core foam blocks were subsequently covered with more glass fiber

weaves to form the bottom / interior skin of the segments, which were then covered with a foil for the next vacuum-injection. In the actual production stage of vacuum injection, polyester resin was continuously injected between the blocks, forming the GFRP glass fibre strip stringers, thus creating a structural connection between the upper and the lower skins after curing.

The foam block arrangement was from now on in fact only used as a lost internal mould. Originally, its function was foreseen as a stiffener of the upper surface to ensure that a solid backing is available behind the upper skin, just in case an unfavorable local load was to occur on the outside of the upper roof skin. Local buckling of the top layer of the GFRP sandwich, possibly caused by pre-assembly and future maintenance works, would be prevented in this set-up.

After a check by the head of production on the finalized composition and on the required recesses, the entire sandwich core was covered by the glass fiber mats, which would become the underside of the wing. Finally, on top of these fibers, plywood was installed on all building related interior areas, to which fire-retardant plaster material would be applied by hand in-situ, while working of temporary scaffolding towers. The plywood was also applied to smoothen the landscape of all separate components during vacuum suction. The plywood was equally spreading the pressure in the vacuum process, because of its thickness, and acted as the contra-mould in the process.

The permanent package was now fully completed and was wrapped in the next plastic bag. After this, the part of the mould representing the exterior area of the building, which was not yet covered with plywood, was now covered with temporary plywood as well on top of the vacuum bag for smoothening purposes. Then another bag was required to cover the whole and pumps were started and the vacuum process began, which pulled the resin through all fibers and empty spaces. The hardened resin in combination with applied heavy glass fiber strings, created the missing parts of the bulkheads between every two inserts. The layout of parts and the final vacuum suction took the HCI team another two days.

FINISHING OF THE SEGMENTS

The next two working days of the HCI team consisted of finishing the panels. First the panels were unloaded from their moulds. These were deliberately broken into parts, as they would not be re-used. The former location of the steel inserts on the moulds was clearly visible in the presence of large holes. The polystyrene simply melted away at the location of the insert, since this part attracted the heat of the isotherm reaction of the hardening process of the resin. This only occurred in the moulds for the Library wings. After that something clever had to be thought of, because the moulds for the Central Body were intended to be used twice: once for the roof cladding and once for the ceiling cladding. As the set-out shows, the finished roof and ceiling surfaces of the Central Body were derived by vertical copying rather than 3D-offset. Simply saving ~20% or 250 m² of moulds required for the entire project. The outcome was to add a chemical to the resin, which would tune down the heat peaks of the hardening process.

After cleaning the enormous pile of polystyrene wastage, the big M36 / M48 threads for the hoisting eyes were cleaned as well as the threads of the 8x M20 holes of each side insert for the connection to the concrete wall. The hidden inserts were relocated by metal detector and marked in black on the outside of the panel. Using a small plywood template with the actual size, these markings were done in no time. Of each panel the weight was recorded in order to do check-ups with theory. Of course the quantity of materials of each panel was fairly accurately known, with exception of the amount of resin. Obviously, HCI had to keep adding resin in order to saturate the product completely. Apparently this was somewhat hard to predict and appeared to be abundantly more than thought of by the composite engineers in theory.

After finalizing the check-ups, the form of the edges of the wing had to be confirmed as a continuous free form 'beam' along all three sides of a Lower Wing. A few options were thought of to materialize these noses and like many other things, the first idea here too appeared to be the best. Finally, they were made like extrusions in its designed round cross-section in lengths of 4m. The material used is similar to the spongy yellow foam that can be found as filling inside the seats of a car. Its flexibility allowed us to bend the nose in all directions necessary. This 'fake' nose, when it comes to structural properties, was able to cover possible deflections in positioning of neighboring panels. Two sides of an Upper Wing follow the cylindrical contour of the concrete walls below. These sides were therefore developable and pre-cut out of plate material and connected to the sides of the wing using wedges to establish the correct local angle. Both the cylindrical and the rounded noses were laminated to the connecting panels. After these experiences, HCI trusted to add the noses of the Great Hall wings directly on-site, without further fitting of panels on frames. Having witnessed the entire situation and process on-site, the concept of the noses and the moment of adding them should be rethought for a next project, in order to reduce the labor intensive activities on the site. Finally the panels were taken of the assembly frame and ground smooth on all sides. As with many things, composite production activities in the factory are much easier to do and lead to better quality and more efficiency than composite site activities.

Parallel to the production of the first complete series of segments for one complete wing, we considered it would be wise to pre-assemble all segments of one wing to a complete wing at the factory site, in order to be able to judge whether HCI could state that they mastered the shrinking of the segments during curing and that they could master the overall tolerances required. This was done at the premises of Holland Composites. Then the question came: how to build-up the entire shell of the Upper Wing of the Library out of its segments and how put to it in its final position on the building? A few concepts crossed our minds, but the idea of a demountable steel frame under the segments, to be connected to the wing got the overhand quite fast. The best scenario was a pin-bed like frame, consisting of many manageable smaller components. This appeared to be a practical solution.

Each wing would be orientated optimally, minimizing the working height. Thankfully, a short study proved that rotation of a wing's final as build position towards the generally horizontal assembly jig position over just one axis, already optimized the overall height by almost 100%.

The axis of rotation stands perpendicular to the direction of slicing / seams; rotating along a second axis to further optimize the overall height would have a minimal positive impact on the overall height, but would complicate all references to a great extent. The advantage of rotation along one axis was quite large, since all supports could stay aligned on parallel floor beams following every seam, which by itself was in fact created by a grid of straight parallel lines projected onto the free form mould surface. Hence a rotation around the axis perpendicular to these joints, would warrant their straightness in plan view regardless of the amount of rotation. Besides that, when the time came for as build control surveys, translation of the as built point clouds into the digital 3D-wing models for analysis went quite easy as well, that is to say for the trained professional.

The first three segments of the Library had been pre-assembled in Lelystad much earlier. The results were confirmed during the first trial assembly of the complete Upper Wing of the Library: to check the general smoothness of the finished surface and to obtain the architect's approval, to install the edges on the sides of the more or less triangular wings, to check the steel components of the assembly mould, to check the curvature and tolerances on shrinkage of the segments, to check the position of the steel inserts by an as build survey and to check the workability of the mould for the phase of on-site pre-assembly. Above all it gave all involved confidence to continue the process. It was found that shrinkage indeed occurred, due to the in plane suction forces onto the many individual items. It was decided there and then that for all other wings, the size of the joints would be set to zero millimeters for production of the segments instead of the designed 14mm. The shrinkage, being fairly consistent and slightly more than the intended 14mm, would provide these seams automatically.

ASSEMBLY FRAMES

For the first trial assembly of the Lower Wing of the Library, a steel support frame composed of vertical posts was made. In this pin bed-like assembly frame, every segment would get four vertical supports at about 500 mm from its ends. These supports were positioned on a well-considered grid, in order for floor beams to collect and align all supports. The length of each support was easily extracted from the computer and brought into production. All wings were fairly manageable, with exception of the Lower Wing of the Great Hall, which appeared quite challenging on all fronts and resulting in a rather complicated steel pin bed. Its sub frame by itself required 6 tons of temporary steel, to produce and erect the wing and due to the large dimensions of this mould, with supports of up to 11 m at its corners, many stiffening beams and diagonal braces were required. It is these extra items that cause quite a lot of additional detailing. In conclusion, this wing nearly required a complete temporary steel space frame by itself.

The Library's Lower and Upper Wings were the first two structural shells that were pre-assembled in Holland on the steel assembly jig, each in about one working day. The experiences with these two relatively small shells, were positive enough to take the risk and build the larger roof shells for the Great Hall directly on site in Israel. This decision was also encouraged by the enormously tightened time schedule, once it was decided that in only a few months time, around Early November 2005, Bill and Hillary Clinton would come as former friends of Yitzhak Rabin's family to open the Rabin Center.

After the first trial assembly of the Upper Wing of the Library a few issues resulted in the decision to build the other temporary steel pin beds differently: building the wing up-side-down. Walking on the spherical shape of the Upper Wing made the composite team decide quite radically to build the wings up-side down, thus to improve the safety of the working situation tremendously.

Another advantage was, that the steel pin bed would support the mould side of the panels. This was the theoretical side, hence better controllable, more accurate and 100% final. The next positive thing was that the individual panels would be a lot more stable on the steel pin bed and gliding only towards its center. On top of this, the volume of the steel frame reduced greatly in the up-side-down situation, thus the amount of temporary steel required for the jig.

All the above mentioned advantages resulted in two major disadvantages: increased frequency of using huge cranes for the turning of every wing and re-engineering of the required strength of the hoisting points inside the wing for this extreme lifting concept. Hence the implications were much greater than simply steering the crane's joystick, as it was jokingly suggested when this idea was born.

After the production of the roof parts of the Lower Wing of the Library, discrepancies between the theoretical drawings and the practical distortions & 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 GFRP components. These components combined had to form the ruthless smooth surface of the complete wing in the end. All aspects were approached in an engineering manner: measuring, analyzing problems and deducting solutions. Analytical and creative technical engineering in the best traditions of the TU Delft made the initial amazing, improbable design solution finally a material reality.

After the approval by the architect the full go-ahead for the production was issued. The remaining segments of the Library wings were produced in the above described production sequence. In May 2005 the two wings of the Library were shipped to Israel.



FIG. 90 Tubular steel frame details of the central body

LIBRARY TRUSS

The 2-dimensional steel truss in the Library located in between both GFRP-wings, is pre-fabricated into two parts with a bolted double sleeve connection at mid-span. The weight of both halves combined is 1650 kg. The upper and lower CHS beam of each part [ø193.7x8] were developed in a free form shape and afterwards developed into different radii. For starters, the CHS beams were rolled in one piece with varying radii, but 2-dimensional. For Octatube this was the first test for the rolling factory. The rolling factory not only rolled, but also cut the tube to size using CNC processes. With the 2D-rolling process, the clamping ends of the tubes are part of the wastage. 3D rolling needs an even larger clamping length than 2D rolling and thus has more wastage.

CENTRAL BODY TRUSS

The next large engineering challenge for Octatube Engineering proved to be the Central Body: the central part of the Great Hall supporting parts of the Upper & Lower Wings and related two bay windows. Unfortunately this central part of the roof had to cope with large forces from Upper and Lower Roof wings, a tubular steel structure was thought to be the only solution to make this span possible and provide adequate support to the structural shells. This resulted in a complex 3D-curved structure using CHS tubular steel members, later to be covered with thin GFRP panels at the top [roof] and bottom [ceiling]. Because 3D-rolling of tubular elements is a rather complex and not fully accurate procedure, the entire digital composition was made in 2D-rolled tubular segments, like macaroni pieces in different lengths and with different radii, which possess greater accuracy. The 3D-curved tubes, situated in the length of the Central Body, at best approaching the desired shape, therefore had to be connected to the more accurately S-shaped 2D-curved tubes in cross section of the Central Body. The entire Central Body was pre-assembled in a first trial assembly near the Octatube factory in Delft before hot dip galvanization.

The structure appeared to be as high as 9,3 m. Hence very labor intensive for the erection team. After painting the individual steel components, the Central Body was reassembled for a second time in Lelystad to check the GFRP skin coverings. Two containers had to be positioned under the steel structure to reach the connections. All individual truss & delta truss endings related to the anchorage onto the concrete walls, the two central column support locations as well as all individual wing connector locations were fully surveyed at this point and analyzed against the computer model. After the full trial assembly in Lelystad, it was decided to build up the final assembly on site in two halves, which would result in a more manageable temporary structure with an internal height of only approximately 3,5 m. After all panels were trial fitted, the structure was demounted and transported to Israel.



FIG. 91 The central body of the Great Hall (spanning ca. 30m)

STEEL COLUMNS

Parallel to the production of GFRP segments in Lelystad, the steel columns and the rotating column heads alias the wing connectors, were produced in the production hall of Octatube in Delft. Besides the load bearing function for the roof, these columns also bear the dead weight and wind load of the frameless glass façades. Production of columns is a routine job for Octatube and not specifically worth mentioning here, the only difficulty being the innovative hidden hinging connection between the columns and the roof: the wing connectors.



FIG. 92 Elevational view



06 TRANSPORTATIONS

WING SEGMENTS

Three options were explored regarding transportation of the GRP-wing segments. Each of these options directly relates to finance, quantities of parts, amount of on-site labor, joint lengths and ways of assembly. These options were studied in an early stage, as they were of major influence in the distribution of the stringers and other reinforcements like the steel inserts:

- 1 Pre-assembly of all segments (small or large) into complete wings in Holland, transportation on top of the deck of a ship towards Ashdod and flown in by a helicopter (position at tender stage, aborted as being too expensive).
- 2 Small segments of approximately 2 m wide, transported on the road in 40ft closed (2,2 x 2,3 x 12,0 m) or 40ft open-top (2,2 x 2,6-3,5 x 12,0 m) containers from Lelystad towards Rotterdam, then put below decks on a ship towards Ashdod and again by truck towards the site in Tel Aviv.
- 3 Large segments of maximum 3,5 m wide, transported on the road using police guidance, either on their sides in an 40ft open top container or in specially made transportation frames (4,0 x 4,0 x 15,0 m), from Lelystad towards Rotterdam, then put below decks on a ship towards Ashdod and again by truck towards the site in Tel Aviv.

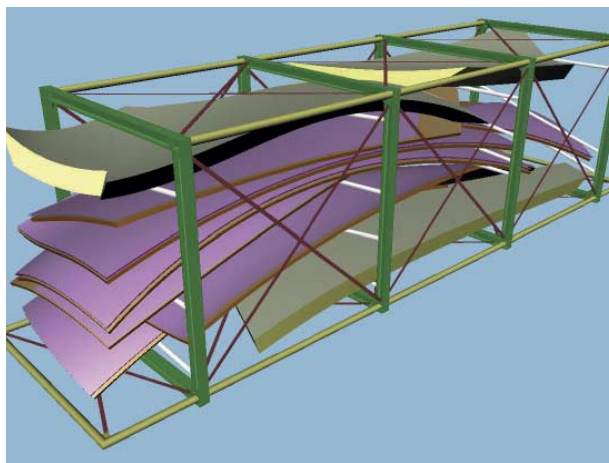


FIG. 93 Proposal for custom transport crate

Dividing the shells into segments was quite complicated. At first the shells were exposed to a projection pattern with a radial subdivision. However, compared to a parallel division, the quantity of panels per wing could only be reduced by one. Quite soon, the parallel segmenting became the favorite option and starting point of further studies. When segmenting each shell, a few parameters were involved. The milling factory could not mill volumes larger than 3,6 x 1,5 x 12,0 m. The choice for small (w=2,0 m) or large segments (w=3,5 m) directly influenced the total cost for transportation, the complexity of the assembly mould and the amount of on-site labor. In both options the length would be 12 m, due to the milling boundaries. The orthogonal grid could not intersect with the many local steel inserts in several directions (facades, trusses) as well as lighting holes for some wings. This caused the large segments to have great advantage, due to more flexibility in panel width / location of divisions. In some areas the length of a segment was limited due to the shell's local curvature, exceeding the maximum 1,1 m height restriction set by the milling factory. This resulted in the introduction of a cross division for all wings, except the Library Upper Wing. Each layout option was of course first discussed and approved by the composite engineers of co-maker Solico, Erik van Uden and Hans Muller, whom determined the minimum distance between the division and a steel insert at 32 mm. In some cases however, the square steel insert was trimmed at one of its corners to allow for a division to occur, such as to minimize the amount of wing segments.

Studies for transportation of wing segments were executed in two ways. Each shell was built as a scale model 1:50 of GFRP, including its division lines into segments. These small models were sliced and put together in mini transportation boxes. The other exercise took place in a digital environment. The transportation crate and every wing were available in 3D. By slicing every shell and stacking them in a specific order, the transportation plan came about using a minimum amount of transportation volume. This resulted in 4x transportation frames of 4,0 x 4,0 x 15 m combined with 2 x 40ft open-top containers. This transportation plan reserved for 80 mm space for wrapping materials between every segment. Also additional supports below every 2 or 3 segments were planned for.

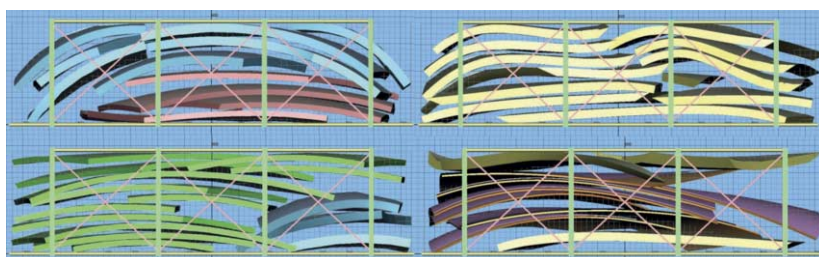


FIG. 94 Arrangement and digital nesting of the segments of the wings in special containers

In May 2005 the two wings of the Library and the Upper Wing of the Great Hall were shipped to Israel in two specially designed super-crates, sized 4,0 m x 4,0 m x 15 m to contain as many segments as possible. Transport using regular freight ships to the harbor of Ash Dod and from there to the site by inland trucking transport. The Great Hall's Central Body & Lower Wing segments followed later in another two of such crates.



FIG. 95 Super crate with the roof segments leaving the production facility ready for shipment in April 2005

In actuality, the segments were strong enough to be stacked onto each other in these frames. Each frame could carry up to 20 tons. In the end, only the 4x large transportation crates were required and the parts in the open-top containers fitted together with the rest in the crates in leftover spaces.

STEEL COMPONENTS

Besides the extraordinary transport of the GFRP-shells, the 3-dimensional steel structure of the Central Body was also exposed to transportation optimizations. When completely assembled, the size of the boundary box of this huge 3-dimensional steel structure is approximately 9,4 x 9,2 x 30 m. Considering transportation volumes, the position of divisions was already taken into account during the early stages of the development of the Central Body's steel structure.

In short, the 2D-truss and the 3D-delta truss were each separated in 4 parts. The discussion for this mainly focused on 2, 3 or 4 parts. For transportation purposes, both considerations were optional even using 40 ft open-top containers. However, the assembly of the Central Body into its final position, which required a division at mid-span of its 30 m length, resulted in the choice for 4 parts. By leaving out 2 divisions, the option for just 2 large parts would remain, in case of special transportation.



07 SITE ASSEMBLY & INSTALLATION

THE SITE

The site of the Rabin Center has 2 main entrances. In the past and in the current situation, visitors enter the site from the 'back' of the Center, via a street at the North side called Chaim Levanon. On this side of the building everything was already finished and a porter opens the gate. On the other side, the South entrance along the Rokach street, only trucks, cranes and lost visitors entered the site, from where the wings can be viewed beautifully from all directions. The building itself was already partially operational. The offices were decorated and in use and some of the spaces were rented for the purpose of military education, important dinners or presentations. The office area together with the museum, the Library and the Great Hall, are located on top of a bunker. This post-war bunker, with its two-meter thick reinforced walls, contains five huge turbines, which could supply the entire city of Tel Aviv of electricity in case of war. Hardly anybody had knowledge of this. One of these turbines will be fully renovated and put on display for visitors to this memorable museum.

During the site works Octatube was the only contractor, to be allowed to use the bunker as cold storage and yes, living room for the installation team. The composite team of co-maker Holland Composites and their local workmen lived there quite intensively from June 2005 until November 2005, eating their humus sandwich under the spying eyes of mice, flying bats, pigeons and the occasional crunchy cockroaches. They used this space as well to store many chemicals, glass fibers and other required materials. Besides the bunker, a white painted closed 20ft container was installed in the parking area in front of the building for specific types of chemicals, as the norms for their safety require.



FIG. 96 Valley assembly



FIG. 97 Hill assembly

The building site activities were generally characterized by juggling with tolerances, the high summer temperatures and working at great heights. This chapter extensively deals with tolerances as the most intellectual challenging problem.

CHALLENGING TOLERANCES

This high-end project knew quite a few complexities as explained in the text. For learning purposes of all interested readers, these are extensively discussed throughout this book. However one of which passed through all phases as a red line: controlling the tolerances in the measurements of the free form products as well as their relation to related support structures. With just one basic question: which tolerances are necessary for each phase? And with just one basic fear: will the wings fit to all connection points during assembly? Nobody had any experience; it was anybody's best guess until installation. Engineering logic had to lead the best possible way forward.

In order to maximize our chances for success; frequent on-site measurement controls were executed for many subjects and by several parties. All this information was gathered and analyzed by one central person at Octatube: Sieb Wichers, the detail & construction engineer. He was the only one to know every position in the project from his engineering work and therefore he was capable to establish the required flexibility of each component. Being entangled by the project and visa versa, he was part of the actual measure controls on-site in Holland and in Israel. In this kind of projects, it can be quite risky just to receive information from different parties for analysis, trusting blindly on the measuring actions and the product. Merely trusting other parties in precision and completeness of their measures without supervision was no option. The project, being under pressure of time and money, had to be correctly executed in one go, the first time right.

In Holland, VDS Landmeetkunde executed the measurement control of both Library wings and the Central Body. In Israel, Greenstein was invited for the final measure control of both Library wings and Nachmias provided the 'as build controls' of the concrete walls, anchors and both structural Great Hall wings. Both Dutch and Israeli measuring parties were guided by Octatube's construction engineer, both while taking the actual measurements as well as executing the computational analysis of all spatial points. The survey itself and its computational analysis were quite tricky for both Lower Wings, since each of these structural wings had wing connector interfaces on both sides of these wings, while the Upper Wings were only structurally connected from the underside. This caused for some challenges during the survey by generating extra external reference points to link the two sides of the shell. For all wing surveys in general, reference points located on the rough outdoor terrain / work floor were linked to known points on the perfectly leveled steel pin bed, which was then linked to the wing segments. Using these frames as part of the survey helped greatly in the digital analysis. Besides these digital measures, simplified cross checks were executed in each phase by hand as well.



FIG. 98 Pre-assembly of panels for Central Body



FIG. 99 Pre-assembly of panels for Central Body

TOLERANCES AND THE NEUTRALIZATION REGIME

The connections between the individual segments can be divided in connections in length and in width of the segments, both of which have a structural function. The prefabricated recess along the panel-to-panel edges resulted on-site in a rabbet of 220 mm wide and 15 mm deep. In this rabbet a 200 mm wide and 6mm thick prefabricated reinforcement plate was installed, constructed of high-density glass fiber meshes that have been vacuum injected with resin. This reinforcement plate is permanently fixed with epoxy glue, while temporarily clamped by screws for curing purposes of the glue. The screws were later on removed to avoid any risk of rust stains occurring on the final surface over time.

Positioning large [120-320 m²] free form wings directly from the crane onto the column heads or wing-connectors with their adjustable shaft and connection plates, could only take place accurately by following the theoretical drawings. These drawings remained the decisive means of coordination and communication. In all phases of engineering, production, pre-assemblage and final positioning, the theoretical drawings were always present and compared against 3D-survey data before any actions were taken. This was the only assurance that in the end the free form wings would fit into position.



FIG. 100 Hoisting of the Great Hall's Upper Wing



FIG. 101 Hoisting of 2nd half of the Central Body

Neutralizing tolerances for different components is an adventure in itself. Building parts were simultaneously produced in locations across the world. In this project the steel was manufactured in Delft, the glass in Luxembourg and Belgium, the polyester segments in Lelystad and the concrete in Tel Aviv. The concrete showed the biggest tolerances of up to ± 150 mm, the inserts & wing connectors allowed for ± 57 mm, the seams between the roof segments ± 12 mm, the seams between the glass panels ± 5 mm, a cast-in anchor group ± 5 mm and a single anchor within the group ± 1 mm. And all these and many other tolerances had to be foreseen to be able to be neutralized in their principle detail design and correctly followed through during production, assembly and installation phases. Tolerances in the different stages from design, through engineering and shop drawings to prototyping, production and building on site govern the success of each prototypical free form project. The geodetic supervision during the process of production and installation has grown in its importance since Bilbao's first free form historic explosion.



FIG. 102 Valley assembly of Great Hall's Lower Wing



FIG. 103 Steel pin beds for HG's Upper & Lower Wings



FIG. 104 Installing the last panel for the GH's Lower Wing



FIG. 105 Hoisting GH's Upper Wing from its steel pin bed

Having arrived at this point, one has to remember that the success of Henry Ford in the automotive industry was not the running belt. "Ford's 1908 Model T was his 20th design over a five year period that began with the production the original model A in 1903. With his model T he finally achieved two objectives. He had a car that was designed for manufacturing, as we would say today, and also was, in today's terms, user-friendly. Almost anyone could drive and repair the car without a chauffeur or a mechanic. These two achievements laid the groundwork for the revolutionary change in direction for the entire motor-vehicle industry. The key to mass production was not – as many people then and now believe – the moving or continuous assembly line, but the complete and consistent interchangeability of parts and the simplicity of attaching them to each

other. These were the manufacturing innovations that made the assembly line possible”

[From Womack et al, *The Machine that Changed the World*].

In similar projects where buildings based on a free form design had to be realized (for example: Town Hall, Alphen aan den Rijn, see www.mickeekhout.nl), the total costs involving geometrical surveying from prototyping and productions up to assembly and installation were about 3% of the contractual turnover: a serious amount of man hours! The building industry has finally arrived at the international industrial level of 3D-design of components, boosted by the inevitability of the technical compositions of free form architecture. From now on the different ingredients or components of free form architecture that are made in lots by different co-makers / subcontractors, sometimes in a number of different locations all over the world for just one project, put the building industry in line with the automotive industry, only just a 100 years later. This is helped by the changeover from the concrete and bricks technology where joints can always be adapted to fit on the site, to the more industrial high-technology where all components have to be fitted specifically in an industrial mode, so with outspoken and very accurate production tolerances only. Once Henry Ford could force his component suppliers to produce and supply components with fine and accurate (and only negative) tolerances, he could avoid the adaptation of components on the assembly floor (in the building industry: on the building site), which made the difference between the former automobile ateliers where cars were hand-fitted after most of the time was lost in refitting the components. An industrial and almost ‘blind’ assembly only focused on the assembly activities and not any more on the component care. From that moment on, Ford could even deploy a running belt as the continuous production assembly base.



FIG. 106 Preparation and hoisting of the Upper and Lower Wings of the Library



FIG. 107 Assembly of the roof segments by gluing and bolting glass fibre polyester plates on the seams before applying the finishing layer

PROCESSING AS BUILD CONTROLS

An interesting fact of the Israeli measurement controls was their choice for the location and orientation of the base point. In case of the Rabin Center, as well as for all other projects in Israel, the base point was hidden in the desert somewhere in the South of Israel. All point clouds received from them use this fixed coordinate. The base point [0,0,0] for the local grid of the finishing floor level for both halls of the Rabin Center therefore started 213 km (!) away from the global base point at [131.182.790, 167.792.362, 31.000]. One can imagine, when opening the AutoCAD-files, one could see just two tiny dots, showing something on at the lower left side [the base point] and the upper right side [the building's grid] of the computer screen. Besides that, the local grid appeared to be rotated 21,24°. Combine the previous with the fact that each of the two halls appeared to be erected incorrectly compared to the building's grid. Therefore each point cloud of one hall had to be moved and rotated as much as possible towards theory, in order to minimize adjustments for production and maximize standardization, where applicable.



FIG. 108 Detail of wing



FIG. 109 Details of central body



The above might seem unimportant as one probably would think that the computer nerd easily orbits [= move + rotate + zoom] around the geometry towards any desired position. Unfortunately every time, the engineer had to rack his brains: in what direction was which part rotated using which points and in which sequence? Resulting in all kinds of extra operations, which, without doubt, contain errors and/or misinterpretations. Leading up to double checks and overcautious operations in order to correctly read and process all [Israeli] as build controls of the building or any of its components. Internal arguments between the detail engineer and the fabrication-drawing engineer were quite often necessary to avoid all kinds of possible misunderstandings or doubts, resulting in discussions over and over and over again.

LISTING OF MEASUREMENT CONTROLS

Many pre-cautions and post-measurement controls were executed on various building components in every building phase on the site: digital and by hand as double check or whichever was best suitable for the challenge. The same was done for productions in the factory of the composite segments, the steel structure, the construction components and the glass panels. Free form technology is heavily dependent on measuring and re-measuring, pre- assembly and post-assembly, otherwise nothing fits, following the Law of Murphy. To the reader, who as an architect perhaps may have little knowledge about tolerances, a good understanding of this subject is of great importance. The most important on-site measurements for this project are listed below in chronological order:

- 1 Digital measurement controls [DMC] on pre-cast steel plates on walls;
- 2 DMC for orientation and welding of the base plates on concrete walls;
- 3 DMC of the welded base plates, threaded bars in the floor and walls;
- 4 DMC of all pre-casted anchors in the floor;
- 5 DMC of the structural ACRO-scaffolding towers in relation to main columns;
- 6 Main lines, insert base points and assembly supports on the PS-moulds;
- 7 Markings were added by hand on the outside of all separate mould parts;
- 8 Geometric controls by hand on the polystyrene moulds;
- 9 Leveling the assembly mould with a self-leveling laser machine;
- 10 Cross checks of the assembly frame by hand in floor plan by triangulation;

- 11 Checking the predicted deformation of each wing during hoisting;
- 12 Checking the flexibility of each wing perpendicular to its surface;
- 13 DMC of the composition of shell parts on the assembly mould for every wing;
- 14 DMC of distances between inserts on shrinkage and misplacements of inserts;
- 15 DMC of distances between inserts of adjacent separate panels;
- 16 DMC and by hand of the wing by checking inserts in triangulated pattern;
- 17 Circular markings at insert center points on each wing before hoisting;
- 18 During hoisting measuring heights of 3 connection points to the floor level;
- 19 During hoisting measuring the moon-like shape of shifted of insert plates by hand;
- 20 DMC of 3D rolled CHS beams for the production of the Central Body;
- 21 MC by hand of each 2D part of the Central Body's steel;
- 22 MC by hand of Western half of Central Body to fit to the Eastern half.



FIG. 110 Connection of the segments to form one continuous wing

JUGGLING WITH COMPONENT TOLERANCES

Never before, the composite co-maker HCI had made such huge free form products, looking good both from the inside and the outside. Besides that, each wing as a product consisted of several parts to be connected and finished on-site to fit many underlying connection points instead of one controlled situation in the factory. The quality assurance was done by the technical director of HCI Pieter-Jan Dwarshuis himself, who was the master composite craftsman on the job, including on site. All together, HCI was quite unfamiliar with tolerances, how these are build-up, when which parts of the total tolerance should be used and how a building site would influence the production quality. The tension between factory based company and a site based company is clearly noticeable and should be addressed by specialist producers who have to complete their products. In their eyes they do not speak about pre-fabrication, but rather of post-production on site.

ACTUAL TOLERANCES

Reference points / lines are required to determine tolerances and deflections from theory at certain moments during assembly. However, the best moment to think of the most useful possible reference points and lines for freeform objects is just prior to production, during engineering of the component details and their fabrication drawings. In this case for example milling files could contain required references, which could be projected on to the mould perfectly using the CNC- machine, without losing any tolerance there.



FIG. 111 Lower Wing of Library

It is good practice to know that the total project tolerances are composed of drafting and modeling tolerances, production tolerances of the different components, the assembly tolerances and the positioning tolerances for installation. All of these tolerances have to be met or neutralized in principle in the engineering phase, have to lead to zero or negative tolerances of components that have to be assembled via Quality Assurance & Quality Control (QA & QC) and have to fit from one component to the previous component [substructure] in their connections in the agreed plus/minus tolerances. On top of this we have the deformations of the load bearing structures under acting loading cases.

The following summary shows tolerances used in steel parts and GFRP segments for the wings of the Rabin Center.

- Wing connector: tolerance in Z-direction (± 25 mm) + conical rotation of the head ($\pm 5^\circ$) + possible rotation around Z-axis (360°);
- Wing standard inserts: tolerance in all directions in plane of the wing (± 57 mm);
 - Sub-tolerance in 3D-model of the engineer towards milling files (± 1 mm);
 - Sub-tolerance base point on mould by milling machine (± 1 mm);
 - Sub-tolerance in rebuilding the mould at HCl (± 5 mm);
 - Sub-tolerance for positioning insert on mould (± 5 mm);
 - Sub-tolerance due to vacuum process for production of panel (± 15 mm);
 - Sub-tolerance for positioning panels on assembly frame (± 10 mm);
 - Sub-tolerance for re-finding and marking of the inserts with metal detector for circular markings (± 5 mm).
- And after the moment of measuring the separate panels on the assembly mould:
 - Sub-tolerance for position connection points steel structure (± 5 mm);
 - Sub-tolerance for assembly of wing on structural connection points (± 10 mm).
- Wing side inserts: tolerance in Z-direction (± 5 mm) + tolerance in plane of console connection (± 50 mm) + as-made welding position console;
- Main facade columns: tolerance in Z-direction (± 10 mm) + as-made base plate + rotation around anchors / Z-axis ($\pm 1^\circ$);
- Short columns: tolerance in Z-direction (± 25 mm) + as-made base plate + rotation around anchors / Z-axis ($\pm 1^\circ$);
- Wing dimensions: tolerance in span between walls (± 25 mm);
- Main facade upper panels: tolerance in Z-direction of the glued U-profile (± 30 mm);
- Clerestories + bay window panels: tolerance in Z-direction of the glued U-profile (± 10 mm) + as build production.

The on-site measurement control of each wing was implemented into the 3D engineering models and 3D drawings. Since the measurement control was done in the up-side-down position of a wing and since on-site reference points could never be foreseen at the time of engineering, the grid of the assembly mould (tolerance ± 5 mm) became the reference for this implementation. The point cloud was orientated as precisely as possible in the 3D-model. An assembly plans was extracted from this model, by viewing it in top view, as the wings would be assembled on-site. Every measured point was assigned a circle in the size of the perimeter of the connecting wing connector. This resulted in expected specific 'moon-like' shapes, visible on-site during assembly at each connection. The assembly plan showed the expected position and 'width' of the moon for every assembly point, which appeared to be correct by ± 10 mm.

The glass facades are a separate story in itself, but were based on more than a decade of experience with designing and realizing of frameless glazing. The original design was a standard mullion façade, which was redesigned as a frameless glazing façade. This part of the building was not interesting as an innovation compared to the composites sandwich wings.

All insulated glass units of the main façades had to be installed before the formal inauguration of the Yitzhak Rabin Center at the 14th of November 2005. This was starting point for the early order of these glasses, for which the delivery time exceeded even 4 months! The glasses were shaped, fritted, coated and laminated, far away from the site, which made them quite special for production. At this point in time, no wing was assembled on-site, which made it impossible to measure the actual dimensions of the panels connecting to the wings. A specific custom 'banana-shaped' U-profile was developed, which could follow the line of the wing, hide its possible Z-deflection and structurally carry part of the wind forces on the most upper glass panels. The inside free height of the bananas was directly related to the tolerance of the wing connector and was therefore set to ± 30 mm. This way the shaped panel, constructed out of straight lines, remained uncomplicated.

SAFETY SYSTEM OF THE CENTRAL BODY

On the Central Body a total of 34x eye-pads were installed. These safety and working eyes were differently connected to the GFRP-shells compared to the structural wings. In this case inside the hollow Central Body, hidden stainless steel backing plates were installed and extra long stainless steel countersunk M8 bolts were used. After drilling 3x holes for every safety eye, the holes were filled up completely with glue and the position of the eye-pad and the backing plate were locked, using a two component Spabond glue before installation.

Rope workers always need these safety eyes, to be like alpinists active on the highest points to create maximum safe working circumstances. Once hooked on, the rope worker uses three lines. One line is the working rope, which connects to two eye-pads. The other coming from the same direction and also spreading its forces to two eye-pads is the safety line. The 3rd one comes from the sides and is the so-called helping rope for 'horizontal' positioning, to provide stability against gliding to the left or right.



FIG. 112 Alpiniste workers on polystyrene skin



FIG. 113 Upper and Lower Wing of the Library

POLYESTER WORKS FROM SEGMENT TO SHELL

All recesses of each panel were thoroughly grinded and dusted for optimal gluing results. With two component Spabond glue and temporary screws for pressure, HCI started to install 200 mm wide & 6 mm thick pre-fabricated glass fiber plates in lengths of one meter on the lower side of the seam: the mould side. A small 'factory line' became active. One worker supplied the glue in portions of a few kilo, while another worker spread it over the surface of the plate. The next one bringing it into location and holding it, while the professional of HCI screwed against the wing, in such a way that the glue just came out along all sides. In total about 300 m of stretching seams were to be glued for the four structural wings. About the same amount of stretching seams were present in just the Central Body. However, there is a big difference between the two types of seams. The structural seams were 200-300 mm high and had to be structurally glued and finished on both sides, while the cladding like segments of the Central Body only required gluing and finishing on one side: the exterior side. The table below shows the effect of the extra division in transverse direction on the shell area per stretching seam. The Library Upper Wing was the only one of the four shells, without a transverse seam. Logically, the ratio area / stretching seam for this wing is 3,4 m²/m, which is the same as its average 3,4 m segment width.



FIG. 114 Connecting two segments with the prefab glass fiber 'preprag' strip with epoxy glue and screws for temporary tightening during curing

Again in case of the enormous Great Hall Lower Wing, it was quite time consuming to supply the glass fiber plates for seams located in the highest areas. A few days later, the glue hardened completely and all these thousands of temporary screws were taken out to avoid any possible future corrosion to occur on the exterior visible surfaces. The following step was to fill all spaces between the top surfaces of the segments and the connection strips along the joints with a filler.

Of course, after the filling process the edge of each segment was polluted with small hardened filler remains, which had to be grinded off. Now the not-mould side of all seams could be structurally glued. However, since the recess of two connecting panels was made by hand and therefore not always exactly the same, on some positions the pre-fabricated glass fiber plates could not be used. For these locations, the seams had to be laminated by hand layup method. Seven layers of glass fiber mats were applied, alternating different fiber directions.

Simultaneously, the three sides of each wing received a serious 'nose job'. The edge as a separate 'nose' component covers up displacement errors occurring between the individual segments. Smaller and bigger reconstructions of the nose were required, mainly around the dividing seams. This work was only cut out for a professional polyester master. It took him about the same amount of time to apply and fix the perimeter edges as for the rest of the team to completely finish the structural seams of a single wing. In fact, the nosing job appeared too labor intensive as site work.

The seams between the segments were grinded for sufficient shear force, filled with abundant polyester and wiped off. In order to come to a smooth finishing of the seams at the exterior surface, the filling process had to be executed three times, due to shrinkage of the polyester material. In between each filling step and after the last filling action: grinding, grinding and more grinding was required to get rid of miniscule remains. Finally, the entire wing surface had to be grinded gently before applying the final gel coat layers. In two days per wing, two layers of coating were applied to get a thick saturated water resistant finishing in RAL 9010. The plywood ceiling was given a white primer for the later-on in-situ applied fireproofing layers of plaster by yet another Dutch team.

TURNING OF THE WINGS

And then, finally after thousands of hours of grinding the most spectacular moment arrived: the turning of the wings. As mentioned before, the wings were originally not designed to be flipped 180°. Thorough discussions between the Dutch teams were held and calculations re-made. The 1:50 scale models of the wings played a stimulating role. We could play with the wings like puppets on a string. In conclusion, the internal components of all wings appeared of no worry what so ever. The design of both Library wings remained unchanged. The only obstacle appeared to be the hoisting eyes of both the Upper and Lower Wings of the Great Hall. Two types of adjustments had to be made. Firstly, the designed eyebolts had to be altered to large swivel eyes. Secondly, in case of the Upper Wing the 'pre-casted' hoisting inserts were too small and somehow, the M36 had to be enlarged to M48. This was required for only two of the three hoisting points, which at some point each would carry the weight of half this wing.



FIG. 115 Hoisting the Great Hall Upper Wing

HOISTING OF THE WINGS

In principle all hoisting days were the same. In every case, the wing was hoisted using two cranes. An alpinist rope worker wrapped his feet in plastic to avoid dirty footsteps on the white wing's surface and even put on white gloves. While standing on the wing, he installed plastic around every hoisting eye for the same purpose. At the same time, separate trucks supplied the counter balance for the cranes. For these types of cranes (180-300ton) it takes about 1-1,5h to position themselves and add the required balancing weight. The rope worker connected the 2-point fork cable and the third point to the hoisting eyes and the hoisting started. During the first hoist of each wings, the cranes held the wing in its final position just above the floor. Then the heights of three inserts were measured and their delta heights checked against theory. In a later stage, only two inserts nearby the hoisting inserts used for the cable fork were measured and compared to each other as the 3rd point was fully adjustable, using heavy chains. It was magnificent to see each wing floating just ± 3 m above the floor in a more or less semi-final position. One of the two cables of the 2-point fork was adjustable as well as the single third cable, both using a 10ton sling for a possible fine-tuning for the global position. This flexibility was used in most cases and appeared successful every time.



FIG. 116 Lower Wing of the Library



FIG. 117 Library Wings in place

During the hoisting of the Upper Wing of the Great Hall the site was extremely cramped and there was only enough space for just one crane. Therefore one crane stood aside, awaiting the 'small 250ton' crane to lift the Upper Wing all by itself and to bring it above the pergola of the Rabin Center. After that, the 300ton crane was positioned at the former place of the wing. About one and a half hours later this crane was setup and installed with a JIP in the very tight area directly next to the other one. Finally, the movement of all assembly people, including two rope workers, indicated the start of the next step in the lifting process. While the rope workers climbed up the pergola and higher, all other workers repositioned themselves at various locations on the 22 m high scaffolding. The 2nd crane rose up its

telescopic beam with attached JIP towards the pergola, where it was connected to the third point. Finally, this point would go all the way up in the Great Hall at ± 45 m above the area where the cranes were standing, with a flight of about 55 m. When measured from point-to-point [rotation point crane to hoisting eye] this results in a length of 71 m: a huge crane lifting the 16-tons of deadweight!



FIG. 118 Hoisting of the Great Hall Upper and Lower Wings

POSITIONING OF THE WINGS

In all wings, the steel box inserts were located correctly in the composite segments, i.e. not upside down, inside all wings. Then with much sweat and tears, the holes were manually drilled into the 15 mm thick hidden steel insert after which each hole was threaded. Only then the wing connectors would be reassembled and bolted to the wing. This was done for alternating columns such that the weight of the wing was temporary distributed to adjacent columns.

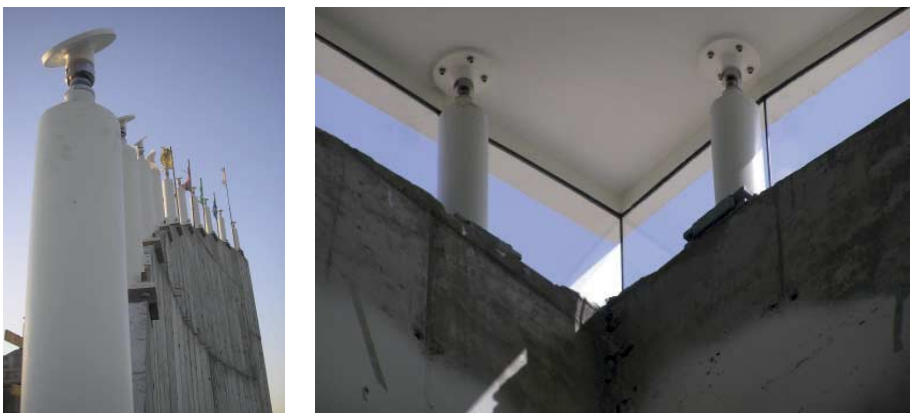


FIG. 119 Ball-and-socket wing connector detail on top of the short wall columns

In all hoisting actions regarding the four structural wings, the circular markings proved to be sufficient to confirm their final position. After touchdown of a wing on its supports, Sieb Wichers investigated the 'moonlike' shape that occurred between every circular marking and the circular head of a wing connector. He compared the installed result against the measurement control analysis drawing for assembly, by measuring the thickness of the moonlike shape at each location. This assembly tolerance drawing was made, using the theoretical wing connector heads and the measurement controls of a wing while positioned on the steel pin bed in up-side-down orientation. The measurement control was implemented in the theoretical 3D-model and orientated until an optimized situation occurred, which would provide maximum tolerance for the site assembly. After a first in-situ check-up, the wing moved again slightly when necessary, according to his advice. Finally, it was late in the evening / early at night when executed movements were suitable and all connections were checked once more.

At each of the wing's corners at least 2x wing connectors were 100% structurally fixed, such that the cranes could be released. Exactly 10 years later after the tragic event, in the night of November 3rd to November 4th 2005, the last of 5 wings, being the Great Hall's Lower Wing, was hoisted in its place, just in time. The cranes were removed, the tent was built and the opening guests could be received. The Clintons were welcomed only 24 hours later at the opening ceremony.



FIG. 120 Library end result, the exterior cladding for concrete wall is still pending to date

FINISHINGS

Two weeks of good weather in December 2005 were predicted and the Dutch composites team decided to use this time for finishing miscellaneous outstanding items for the wings. This included using the Israeli rope access team, Bolt, under direction of rope access specialist Amit Nadav, to lightly grind and recoat all external wing surfaces in-situ using the applied safety eye-pads. A few additional eye-pads were installed in-situ based on the experience of this rope access team.

Finally the Dutch plaster team arrived on-site around April 2006 to literally finish the project with a rough orange-like skin on all interior ceiling parts of the wings. First they wrapped and taped every column, connector and U-profile, before they started a final checking and smoothening operation. Having done so, they applied the first layer of spack called Brander Chrystal by spraying. This layer was then smoothened completely by hand. After that, the second and final layer called Brander Diamant was applied by spraying in one continuous action to get the best 'wet-in-wet' result. Both together resulting in a $\pm 2\text{mm}$ thick fire-proofing layer. In total the plaster operation for both halls took almost 2 months.

CLEANING AND COMPLETION

Finally the finishing touches: all windows were cleaned and along all banana-shaped U-profiles as well as the perimeter of each wing connector a white acrylic silicon was applied.

Then, the interior scaffolding could be taken out and everybody was positively amazed about the result. On 16th of March 2006, the architect Zahi Halberstadt officially visited the Library for the 2nd time and spoke the words: "On first impression, excellent!". Of course, like any other architect would, he mentioned some minor things on his second impression. No harm done, that's how the game is played. He requested to paint the four M12 hexagon socket head cap screws white to minimize its emphasis, to execute some small corrections to the fire-intumescent paint of the curtain wall columns and to clean the cantilevering noses of the Lower Wing, which got dirty due to the rainfall and he wanted to discuss the option of replacing the black silicon in the bananas / upper glass seam by white silicon with the main architect Moshe Safdie, who fortunately decided to keep the black silicon as it was. The 3rd and final delivery at the end of March 2006 for the entire Library was successful on all counts.



FIG. 121 View of the building site on the 5th of November 2005, photographed by Ardon Bar Hama



FIG. 122 View of the building site in April 2006



FIG. 123 Interior view of the Great Hall



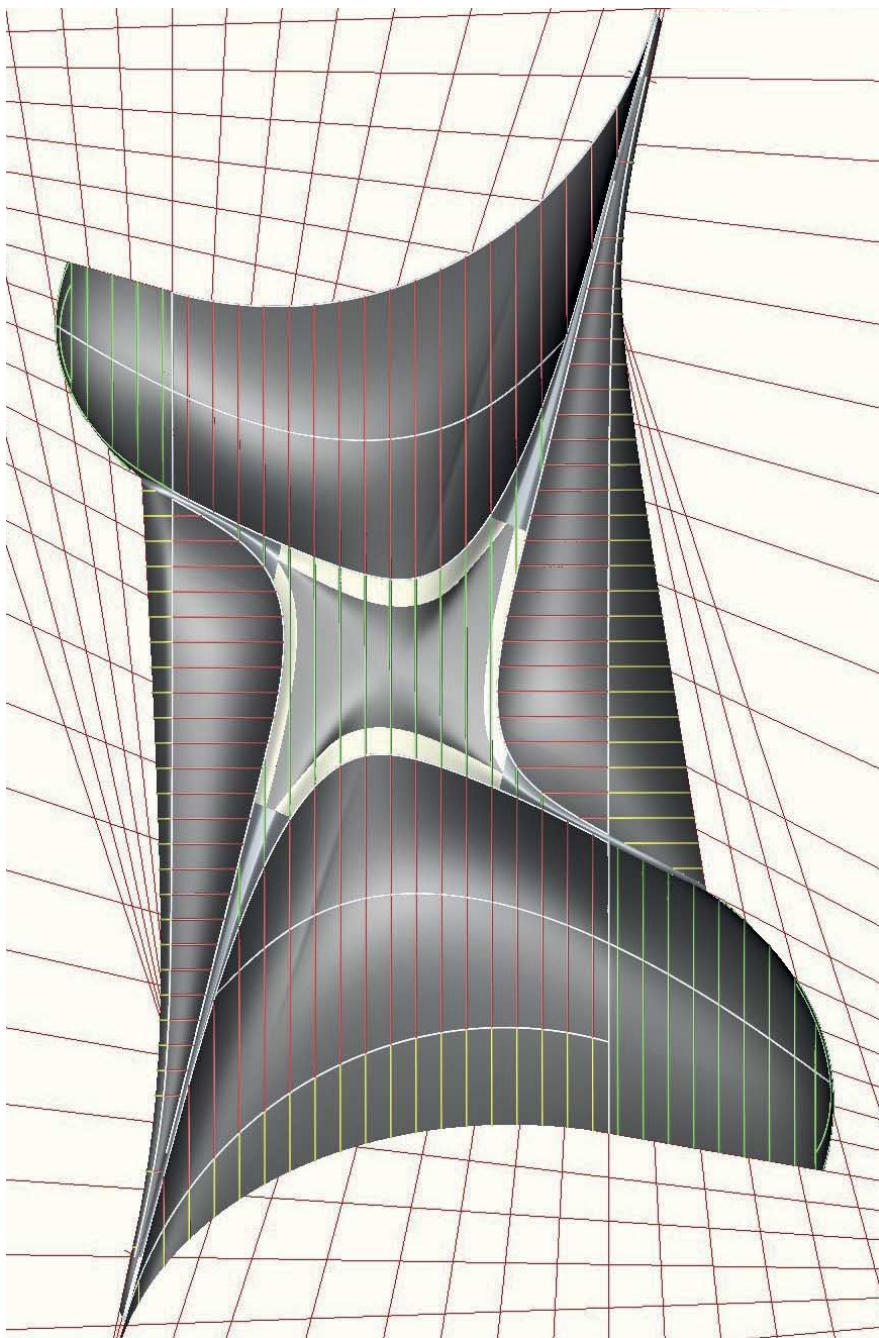
FIG. 124 Exterior view of the building site just after completion of the roofs by Octatube in June 2006



FIG. 125 View on the Great Hall with airborne Ovtatube workers at the tip of the Lower Wing



FIG. 126 The Great Hall interior view



08 THE SLIP-STREAM OF COMPOSITE AND CARBON FIBRE FREE FORM SHELLS

PREHISTORY

The above described sandwich construction shells of the Rabin Center form a renaissance of the shell structures of the 1960s. In those days, due to simple mathematical hand calculations shells were thin, followed the ideal spherical, conical, cylindrical or hyperboloid forms. Results were mostly 50 mm thick concrete shells with only one central reinforcement layer of steel bars. Many shells had a Hispanic origin: Eduardo Torroja, Spain, and Felix Candela, Mexico were the prominent pioneers. The shells were built in countries with high material and low labor costs. In the 1970s, the pioneers retired and the concrete shell fashion stopped. Crafted carpenters retired after that and as a result, making a concrete shell nowadays would become an experiment again. These shells were designed in open and direct collaboration between architect and engineer.



FIG. 127 Works by Felix Candela in the fifties: a timber mould for reinforced steel and sparing concrete on top



FIG. 128 A prototype for a cantilever made of concrete

THE BIRTH OF FREE FORM ARCHITECTURE

Blob architecture, emerging in the late 1990s [Guggenheim Museum Frank O. Gehry, 1998], changed afore mentioned conditions, as the architect designs either directly in scale models or on the computer as if he was a sculptor. The dramatic 3D-effects dominate the architectural thinking. The structural designer on the other hand, is not exactly in a similar position as his views are generally asked, after the architect has created a model or geometry that suits him best, mainly out of visual design considerations. There are usually no direct feedbacks from the engineer on the rapidly evolving architectural design. That is to say the architect has to realize the sculptural whims of the project to a trustworthy architectural structure, which is safe in use. Consequently, the shapes of the new generation of shells are more arbitrary in structural sense and hence have a more unfavorable structural behavior.



FIG. 129 Guggenheim Museum Bilbao, architect: Frank Gehry

Many of these new shells are governed by bending moments due to their unfavorable form and support system, whereas the first generation of shells were governed by normal forces and shear forces in the plane of the shell. The constructional solution for the new shells is in principle the one developed for the Rabin project and now a system solution: a double stressed skin sandwich construction in free form with a structural core. The two skins enable bending moments to be taken, caused by unfavorable loading conditions, column

or support positions and structurally speaking, arbitrary or rare shell forms. We would still call these roof forms 'shells' as reminiscence to the 1960s shells, but mathematicians and methodologists suggest to invent and publish a new name: Blob shells or freeform shells.

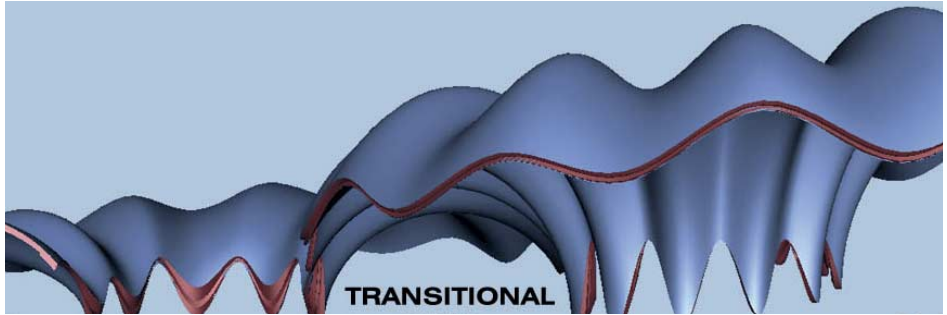


FIG. 130 Schematic roof design for the "Floating Fluid Pavilion", the graduation abstract by Sieb Wichers

The next step in development is caused by the differences in loading behavior between conventional structures in steel or concrete and glass fiber reinforced polyester shells. Blob shells, made of glass fiber reinforced polyester are usually much more flexible, and cannot reach the stiffness and rigidity of conventional structures. For sailing yachts, often pre-stressed by its masts and riggings, rigidity is a relative connotation. As long as the doors and cabinet doors still close and open only a few sailors would mind the distortion in the hulls of their yachts. The consequences and joys of trimming in speed govern.

However, buildings components like windows and doors, often have glass components directly attached to the roof structure. These are influenced by the stiffness of the load bearing structure. Depending of the details, this requires engineering attention. Cantilevering blob-shells can be more flexible than in a conventional structure. The displacement of the 6m cantilever of the tip in plan view [9 m in true space] of the largest wing at the Rabin Center, was analyzed as 100 mm upward and 210 mm downward. The total sandwich thickness being 314 mm. This fits in the general shell theory of Timoshenko, so that the shell still behaves as a shell. Alternatives in steel and in concrete were analyzed to show deformations of respectively 200 mm and 100 mm. The engineering line-of-thought was that a larger movement would be acceptable. Just as long as the movements of the roof under loading do not cause brittle fracture, delamination or other handicaps internally of the blob-shells and as long as the flexibility of the blob-shell does not lead to problems in the technical composition of the building around the blob-shells. For example by crushing glass panels or causing leakages, due to too much movement in the silicone joints,. So no rules yet, but intelligent and responsible building technical engineering, characterize the experimentation phase. The standardization and normalization phase will only follow in 5 to 10 years. No doubt, new projects involving

blob-shells in the future will show up with stricter requirements as to the anticipated deformations in GFRP.

We have to look into other materials as well. Epoxy and carbon fiber is the alternative usually used in the production of high-tech sail yachts. The next generation will be blob-shells in carbon fiber reinforced epoxy. This material is much more rigid and hardly expands as the modulus of elasticity of carbon fiber reinforced epoxy is much lower than that of glass fiber polyester. A much stricter production process, including curing in a controllable tempering oven, which limits the size of components accompany these advantages.

For transfer of technology from the yacht building industry [reference are the black and white ABN AMRO yachts for Volvo ocean race 2005/2006 were built in Lelystad NL using this technology in vacuum injection], the costs play an important role. As the thresholds in the buildings industry are quite low and the price of carbon fiber reinforced epoxy shells are high, clients could prefer to go back to reinforced concrete after studying the price of carbon fiber epoxy shells.

Yet amongst architects a strange mechanism works: the 'first-of-the-block' effect. The first guy of the block who buys a pink Cadillac is "it", the second one is a loser. So at least he has to buy himself a Cadillac of a different colour. Moshe Safdie designed shells that were realized as white shells in original material. The next architect would prefer a black shell to distinguish himself or herself. In this case the famous London-based architect Zaha Hadid designed a free form Mediateque in Pau, France, near the Pyrénées. She is very well known for her free form designs, not only in competition winning designs but also as realized buildings. Her first design images show the 'Mediateque' in white, but the tender documents show a black design with carbon fiber as the basic material. One can only guess that this choice of color and material had their purpose to pronounce a unique design in many respects.

The black roof, about 3x larger than the white roofs for the Rabin Center, had to be made in carbon fiber reinforced epoxy, as we were told in London. Carbon fiber is a stiff and lightweight material that can be used in lightweight structures of large spans with very small deflections. Also temperature loadings seem to have little effects on the deformations of the structures. Not unimportant to counteract the large temperature accumulation in the large black surface.

The weak points in the tender were: nobody had any experience in employing this material on large scale structural shell surfaces, not even in smaller prototypes. The city of Pau wanted a proper European tender process, due to criticism on the previous 7 large projects of the Pau's mayor. This meant: in the first envelope the administrative requirements and in the second envelope the price. A large surface mock-up had to be presented in a size larger than the entrance doors of the town hall, and as the last day of tender coincided with the town's carnival, the central part of town was completely closed off. It was a high-tech experiment, never done before and 3 times larger than the Rabin Center, the carbon fiber weave was hard to find [Airbus has all carbon fiber already engaged for years throughout

Europe], the biggest products were the carbon fiber America cup sailing boats of 30 x 5m and carbon fiber has to be cured in an oven at 100+ degrees Celsius. The architect wanted a seamless solution. In The Netherlands, although the famous ABN/AMRO racing boats of the America cup 2005/2006 were made in Lelystad, no one wanted to burn his fingers on the Pau project. We prepared a tender consortium with Green Marine in Southampton, builders of carbon fiber catamarans and ship hulls. The idea was to build a factory shed of 70 x 40 m², in which the different pre-fabricated segments were to be assembled and after that to be cured for days. The entire roof experiment was priced higher than the budget of the entire building project. The tender price for the roof was about 4 times that of the client's budget for the roof. In hindsight, maybe a blessing in disguise, for this extremely experimental project on a giant scale, the project champion, Pau's mayor André Labarrère, who wanted to realize his 'Huitième Grande Project', died the day after the tendering process closing date. The project was cancelled. The town was relieved. The tendering parties relieved too and satisfied that this cup had passed them.

The design drawings indicate the design proposals by Octatube in carbon fiber epoxy blob shells. In this case it would have been the world's first free form large scale carbon fiber roof. But a good chance that the co-makers would have gone bankrupt in due course of the project. Somewhere in the world an experimental smaller roof should be made, its results and analysis published and maybe then, after a series of smaller projects at last a larger project could be made. Now, in 2015, the year of writing this book, 10 years have passed without such a chance having been reported. The cautious way that Moshe Safdie took by giving the pre-engineering and prototyping order for a mock-up led to a wiser path of gaining experiences and confidence in a new technology and led to a technological successful result.

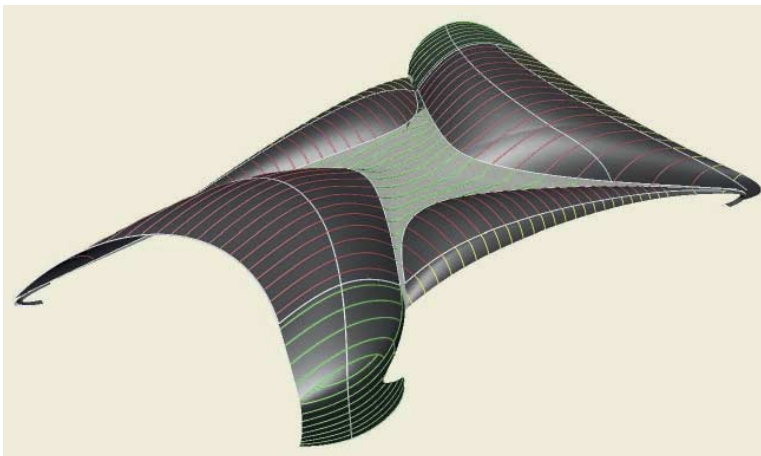
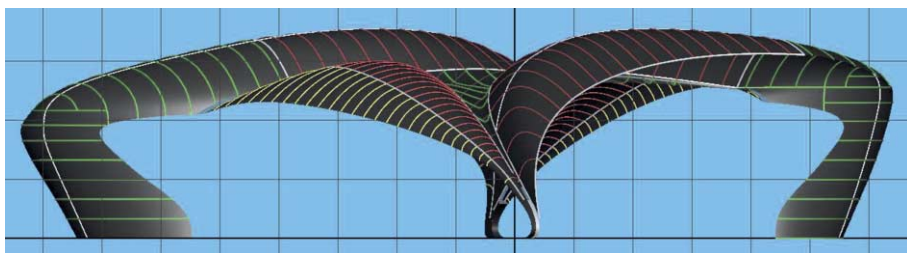
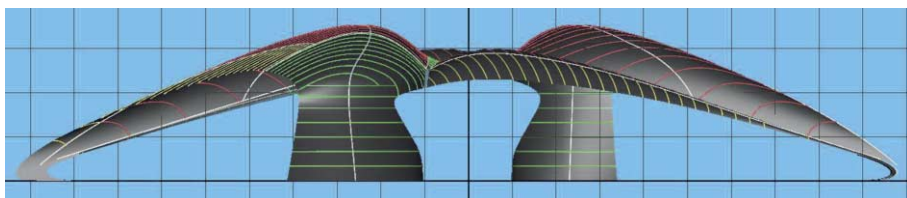


FIG. 131 Roof plans in the tender engineering drawings of the Mediatheque in Pau by Octatube



1



2



3

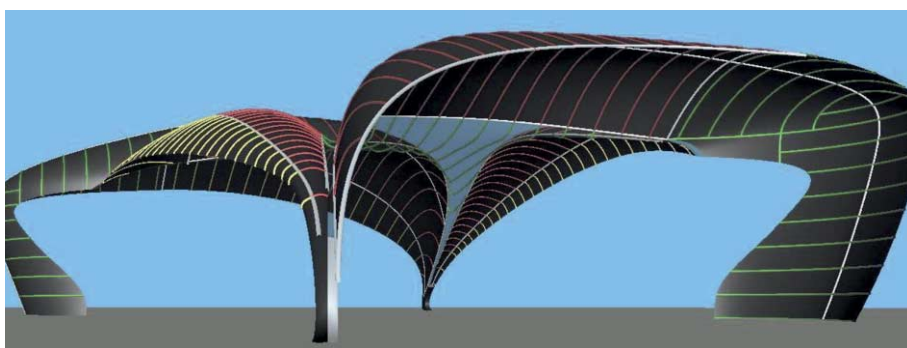


FIG. 132 Different elevations of the Mediatheque's roof structure, architect Zaha Hadid, as designed by Octatube for the official tender

In the slipstream of this project and the publications around it, the Dutch composites industry has grown in the last decade, received attention from Dutch architects, tendered and successfully delivered many composites façades and roofs. A small number of composite companies have manifested themselves in not less that 20 prominent buildings of which a limited number are mentioned here.

One example of a project in which Octatube as the main façade contractor and Holland Composites as the GRP co-maker collaborated again, was the Fletcher / A2 hotel in Amsterdam. Designed by Benthem & Crouwel, the cylindrical shaft of the hotel has 10 rooms at each floor. The exterior walls of the rooms were designed and built as GRP segments, 3 m high and 6 m long. They were sandwich panels with an outer skin of GRP, coated with a duo-colored film, 150 mm of PIR foam core and an inner layer of fire-retardant cement board. The GRP components were made in open hand-lay up method as apparently the most economical to perform. The vulnerability of the cement board for humidity caused the panels to have a slightly larger radius than engineered. This had to be corrected by post-stressing the panels to be fitted on the concrete floor anchors. A slight problem occurred with the seams between the panels. It was unavoidable that the cured panels had different lengths, because of different panel designs with larger and smaller circular windows at different positions, requiring different moulds. Especially for architects and spectators standing on the ground floor, the vertical seams are very visible, especially when deviating from the straight vertical line. The width of the seams between the panels varied from 9 to 18 mm. A remedy would have been a brick-like composition instead of continuous vertical seams, hence not continuing vertical seams. The composite panels carry outriggers, to which the laminated glass panels are attached, produced and printed in China according to a strict pattern and without one single mistake. In all, the learning curve of developing composite components went upward and this production and assembly gave far less problems than in the Rabin Center job.



1 Hoisting polyester segment in facade



2 Facade [picture: Michael van Oosten]



3 Folie screens

FIG. 133 Fletcher / As Hotel, Amsterdam

SINGAPORE'S ART SCIENCE MUSEUM

Hovering above its lily pond, the iconic Art Science Museum is a part of the world-renowned Marina Bay Sands Integrated Resort in Singapore. Symbolizing the welcoming hand of Singapore, with a composition that resembles that of a lotus flower – the Art Science Museum is composed of ten large “fingers” and two smaller lookouts. Each finger-like volume consists of four surfaces: two sides, a top and a bottom. Mainly due to overall building height restrictions and due to increasing internal floor areas, the top and bottom surfaces are each defined by a unique spheroid. The spheroid geometry can be derived from a sphere compressed along one of its axis, in this case: the Z-axis. The resultant elliptical cross section of each surface, only allows for repetition of panels at the same vertical elevation, while using a radial division pattern in plan view.



FIG. 134 Art Science Museum, section and scale model

The design architect Moshe Safdie proposed large white, preferably continuous, seamless surfaces representing the petals of a flower. A few cladding solutions were considered in the early design development stages, one of which was a full composite buildup solution directly mounted on the primary steel structure.

However, when the client was not prepared to pay for full function engineering another solution was sought after and an off the shelf substructure was applied onto the exterior side of the primary steel structure, consisting of structural decking, insulation, cement board, membrane and tapering standing seam sheets. Using standard seam clips, a series of continuous CHS members were fixed in a parallel circular formation onto the standing seam ribs by the Malaysian cladding subcontractor DK Composites in order to mount their specially designed cladding system. This one off system comprised of 12 m long composite panels with optimized varying widths of approximately 600-800 mm. The width of the panel was a result of optimizing the panel thickness as well as limitations of its loading onto the standing seam substructure. The length of each finger surface from the edge near the center of the palm to the tip of the finger is about 60m. Hence, about five rows of panels were required in cross section. Each 15 mm thick panel has an aluminum honeycomb core with a thin glass fiber inner and outer skin. The panels arrived on-site with their gel coat

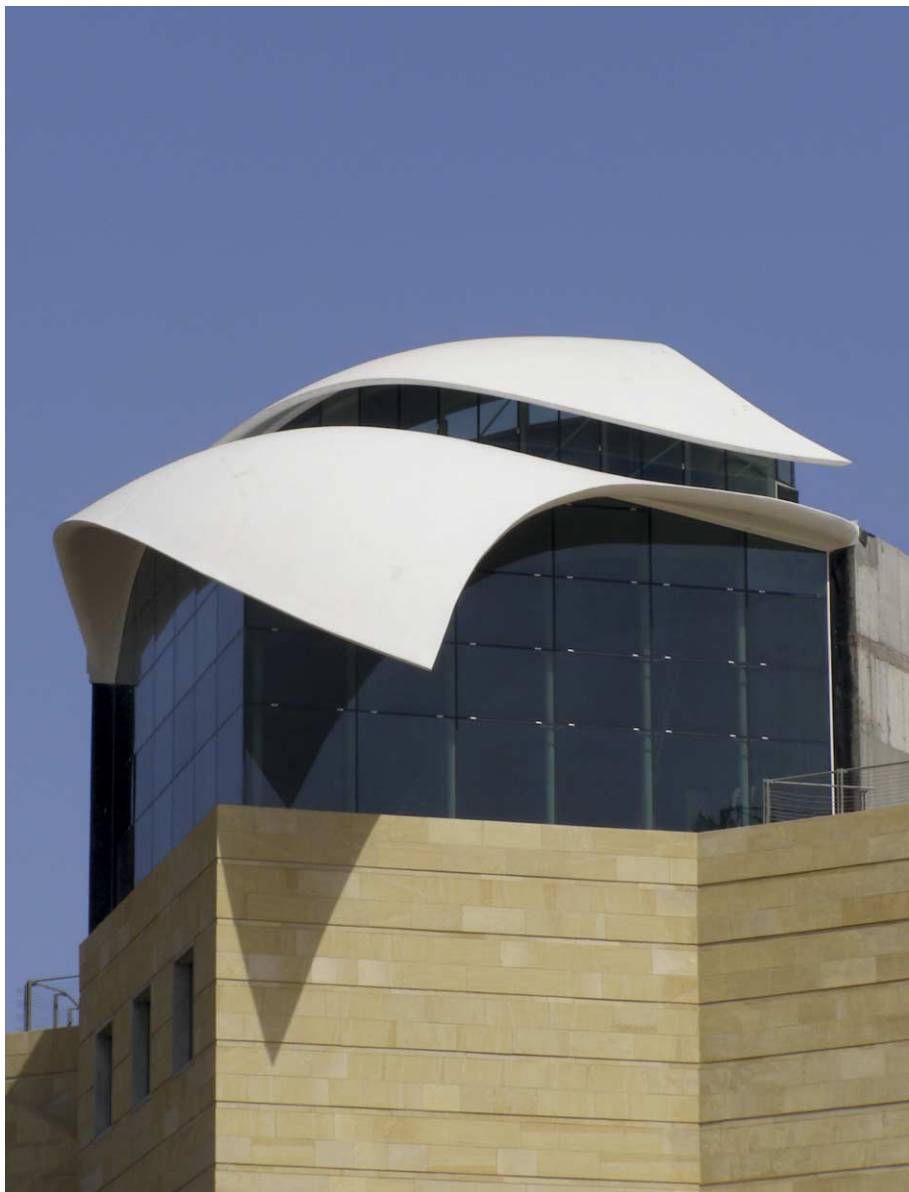
finish. After on-site structural filling of the 3 mm thin panel-to-panel joints only minor grinding along the joints was required. Once the large white surfaces were completed, the expansion and contraction due to temperature changes became compatible with the properties of the aluminum standing seam substrate below.



FIG. 135 Art Science Museum, Singapore

In comparison, the individual thick panels of the Rabin Center with a $\sim 1:3.4$ width/length proportion are very stiff, while the thin panels for the Art Science Museum with a $\sim 1:17.1$ width/length proportion are very flexible and therefore able to follow the standing seam substrate closely to overcome on-site deviations. Where the large Rabin Center wings are structurally restrained at only ~ 20 – 40 points with a significant out of plane added tolerance of ± 50 mm, the Art Science Museum panels are individually mounted along the long sides of each panel at ~ 800 mm intervals with a very limited out of plane tolerance at each bracket. In addition, the edges of the 200–300 mm thick panels for the Rabin Center were less accurately produced due to the experimental nature of the productions, while the edges of the 15 mm thick panels for the Art Science Museum could be very well controlled and accurately produced. For both projects the panels have a constant overall thickness, however for the Rabin Center the skins locally differ in thickness to overcome the local loading requirements within the wing. For the Rabin Center both sides of each wings are exposed to the spectator's eye, while the Art Science Museum only requires a smooth finish on one side of the panels. In order for their purity and beauty to be presented in their full glory, the large seamless white surfaces of both projects must be maintained regularly to avoid stains due to precipitation and other pollutions.

Both masterpieces showcase how the use of cutting edge technologies through reinvention and/or alteration of existing interdisciplinary technologies into a cost-effective solution for the building industry, can make an architect's dream come to life.



09 CONCLUSIONS

This Design & Build process of the free form composite sandwich wings is a remarkable project as an example of innovative component design in all of its consequences. For the occasion of the retirement of Mick Eekhout as professor of Product Development at the Faculty of Architecture, of the Technical University of Delft in 2015, this book was written and published as a proof of eating the pudding on how to work in component design and product development in practice. The project description from practice is published for use in academia so that students and architects can learn about the consequences of extreme innovation; it is also published for the industry to stimulate the composite industry in innovation and realization of their dreams for applications in architecture. The book is a shortened description of the actual initial report on the project, and so the standard building considerations, materials and process activities were left out, so that mainly the innovative aspects remained. A number of conclusions can be drawn from this project:

EXTREMELY INNOVATIVE

This Rabin Center project is by far the most innovative project that Octatube has performed in its more than 30 years of worldwide experience of designing and building of spatial structures and constructions for architecture. It shows that inventions and innovations in architecture are indeed possible, but can come at a high price. It was extremely innovative, possibly too innovative. No less than 9 levels of innovation could be counted:

- Free form geometry of the building;
- Juggling with data transfer between numerous required computer programs;
- Use of glass fibre reinforced polyester as building material;
- Vacuum injection production method for composite shell segments;
- Structural system of sandwich type shell structures;
- Complex interlocking of prefabricated components;
- Main production off shored to a composite yachting industry;
- Complicated site activities out of view at 5000 km from Delft;
- Building in a critical governmental approval environment.

LEARNING FROM EXPERIMENTATION

These 9 levels ensured that the entire process was almost non-manageable in comparison with the usual Design & Build projects in architecture. Too bad that such a great project did not yet receive a runner up, so that the experiences could be reused in an improved process. From the viewpoint of the professor of Product Development the experiences are shared openly with other architects and engineers by this publication.

INNOVATION REQUIRES ASSERTIVENESS

Innovative architecture requires a strict high tech engineering attitude, where one can never sleep, always has to be awake, assertive and think far ahead. Radically innovative projects require the best of skills a high-tech engineer can possess. Yet the innovation game is full of open and hidden surprises and hindrances. In line with 'naviguessers' as the nickname of navigators of the America's Cup, we would propose the nickname 'innoguessers' instead of innovators.

OPEN AND ACCOMODATING ENVIRONMENT

The lack of experience that accompanies experiments has to be compensated, either by more money and time from the client, by complete assistance of the building team (not one party standing alone doing its best to survive in Design & Build innovations) or by an experimental pre-contract for a prototype or mock-up, so that experience can be earned with the proposed technology composition.

INCREMENTAL VERSUS RADICAL INNOVATION

If the Design & Build Company has to perform the project all alone, small steps ahead in the sequence of projects are recommended. It is not wise to stack too many innovations on top of each other: incremental innovations belong to SME enterprises; radical innovations (like this project) require radical budgets, either from the client or from the Design & Build company and its co-makers. If there are no such budgets, there will be only victims of good will. One would wish that more companies would take up a Design & Build approach, take on more responsibility and allow for more innovation in this branch.

DESIGN & BUILD APPROACH

Innovations require a Design & Build approach almost automatically, as many decisions taken in the design phase have a huge influence in the production and installation phase and vice versa. The drawback is that a lump sum price as demanded by clients, automatically restricts the maneuverability of the Design & Build Company to its own experiences and the project's financial borders. In other cases design changes can be quoted for as extra work through variation orders, but in a Design & Build contract this is more difficult, depending of the wording of the contract. In order to be succesful in radical innovation one needs to be steady, stubborn, analytical, creative, good humoured and a bit naïve to endure this game.

USE OF METHODOLOGY

The methodology for product development and components design that Mick Eekhout has developed from his experiences in his projects is also taught as a theory at the Delft University and has been published. In experimental projects this methodical approach steers the respective steps to be taken. It is helpful, as efficiency tool in chaos, but yet not enough to survive. Without a methodical approach chaos will govern.

PRODUCT CHAMPION

Architects with whom the collaboration is considered, preferably are the ones with an open attitude and functioning as a product champion for innovation, protecting the innovation, well knowing that their fate is connected to the success rate of the innovative project. Moshe Safdie clearly has acted as such a champion. Other architects still think that they can demand the impossible and inflict continuous changes in the technical composition up to the very end; They like innovations, but not in their own projects. So architects demanding innovations need to have an open mind.

TRANSFER AND ADAPTATION OF TECHNOLOGY

In this case the interdisciplinary collaboration from Architectural Design and Structural Engineering with Industrial Design Engineering, Maritime and Aeronautical Engineering proved to be essential. It was also a composite enrichment in the field of Architecture and was seen to introduce the renaissance of the composite free form shell as the free form roof shape for the world. Transfer of technology had to be followed by an adaptation of technology, especially as buildings are large, much larger than transport and shipment measurements allow.

NAME AND FAME

Ocatube's name as a small, but super-innovative Design & Build company for space frames, glazing, tensegrity structures, cardboard and composite materials for use in facades and roofs in architectural projects all over the world, has been repeated.

YOUNG COMPOSITES INDUSTRY

This experiment has been followed over the last decade by an increasing interest of Dutch architects for composite façades, made by a small number of Dutch composite industries. From their experiences one can conclude that a good manufacturer not automatically will be a good subcontractor. The difference lies in the tolerances. Buildings are large, much larger than the usual yachting industry products (hulls of ships) and made up of many different components, that in total have to join together with joints in small tolerances. The harmony between in-house productions of elements and additional on-site production and finishing is worth developing before the composite industry becomes a self-supporting contracting industry. On the rear end the composite industry has to develop the site contracting activities; on the front end they may need more design & engineering capacity, in order for architects to see this as a grown-up industry. In order to be successful in radical innovation one needs to be steady, stubborn, analytical, creative, good humored and a bit naïve to endure this game.

10 EPILOGUE



James Carpenter [© Brian Gulick]

As architecture has become a field of its own, separated from the fields of engineering and construction, so the aspects of form and structure have sometimes been pushed by architectural design beyond what may be the realistic boundaries of fabrication. By its very nature the building industry is a conservative one. A proven method will always appear better than a potentially more effective method that is unknown to the industry. As this project proves, pushing the boundaries of the building industry's accepted technologies and methods is an intensive, time consuming and therefore expensive process, but one long mastered by the high performance boat building industry. However the benefits are to the industry as a whole as this new breakthrough proves, with the structural GRP shell now a proven method essential to a free form approach to the architectural form – an approach to architectural design made progressively more accessible to architects through the use of CAD and BIM.

The success of this project depended on close collaboration between Moshe Safdie and Mick Eekhout. Safdie's vision for his free form wing-like roof was not designed without knowledge of how challenging this form would be to achieve and his clear approach to establishing a process that would allow fabricators to develop a method to actually build the structure – essentially a design and prototyping phase for the fabricators and their engineers – was essential to its success. By not defining how to build the winged roof, fabricators could compete on the best, and most creative, design approach based on their experience and knowledge of materials and engineering. Mick Eekhout thrived in this situation because of his firm's fundamental approach to new structures applying a broad yet deep familiarity with design, research and construction.

Shell structures are traditionally thought of as defined and organized by gravity. Free form design undermines the natural structural opportunities of shell structures and, as in this project, push the 'shells' [or non-shells] toward requiring the continuous ability to support any given form. The sandwich composite approach supports this effort.

My own interests have always been diverse: materials, fine arts, engineering. Our work is highly technical but it always starts with the poetics: what is the idea? And how do you engage people? What is the phenomenology of the environment you are working with? I'd say that for the same reasons illustrated in this book, we've almost intentionally avoided being categorized in any one field. Engineering has always been a strong personal interest that is refined and integrated into the execution of our projects. We operate in the middle of those three areas in order to create functional, yet transcendent experience of the built environment.

Part and parcel of revealing the intangible is the need to understand materials, details and construction methods. We are always sublimating material and structural ideas toward the goal of revealing light. This pursuit of looking at light has led to the necessity of understanding materials, structure, construction methods, and working successfully as a team. Our concern is less with free-form structures than with forms that harness nature, merging structural opportunities and embodying the most ephemeral qualities of light to transform the experience of the public realm. The Rabin Center roof structure has established a powerful new opportunity and this book will inspire a new generation of designers to explore form, while hopefully helping them consider the necessity for both a conceptual underpinning to the form and an explicit process by which the forms can be developed.

James Carpenter
New York

11 REFERENCES

Beukers, A., [2003], Licht. lichter, lichtst: lichtheid als gedachtengoed, Delft.

Eekhout, M., [2007] Product Development and Component Design, Multi Science Publishing, London

Kohn W., Rowe, P., Rybczynski, W., Goldberger, P., Sorkin, M., [1996], Moshe Safdie, Academy Editions, London

Tooren, M. van, [2003] Sustainable Knowledge Growth, Delft.

Womack et al, [1996] The Machine that Changed the World, Harper Perennial, New York, ISBN 006097

12 BIOGRAPHY



Mick Eekhout (© Nadine Maas)

Mick Eekhout [1950] studied architecture at TU Delft 1968-1973. He worked at IL in Stuttgart under Frei Otto in Genova and at Renzo Piano's office. Graduated [cum laude] on a complex building [Prof. Carel Weeber] and a space frame system [prof. Jaap Oosterhoff] in 1973. He worked for 2 years in architectural practices and started his own architect's office in 1975. In 1983 he founded his Design & Build company on lightweight structures Octatube Space Structures. Designed and built in one hand were: stretched membranes, shell structures, space frames, glass structures, frameless glazed facades and roofs, cardboard structures, exploded aluminum free form components, glass fiber reinforced polyester shell structures, tensegrity structures. In all structures and constructions incremental innovations are strived at. He leads his group of Octatube companies on projects all over the world and 80 people together with his two sons Nils-Jan and Maxim.

In 1989 he successfully completed his PhD dissertation on his own experimental designs 'Architecture in Space Structures' [cum laude] supervised by Prof. Oosterhoff and Prof. Moshe Zwarts. Was appointed in 1991 as the full professor of Product Development in the faculty of Architecture TU Delft. The focus of the Chair was on high technology components. As a part-time professor he analyzed his innovative projects with his students. In the education he started the hands-on Laboratory for Prototypes. More than 1500 students made their prototypes in the Proto Lab. Research was done on the field of 'Zappi' the unbreakable trustworthy glass-like structural material and on 'Blob Technology', developments to realize free form architecture in different materials. He developed and realized an energy-positive apartment to be built in 4 stories maximum: Concept House. He wrote more than 20 books and over 400 articles. He organized two conferences on technical design with many of his colleague professors from all faculties at TU Delft.

Standing with one foot in 'Industry' and the other foot in 'Academia', he was able to make a master plan for research for the Dutch building industry 'Bridging the Gap'. In 2003 he was made a member of the Royal Dutch Academy of Sciences [KNAW] in which he is the secretary for the 'Technical Sciences'. Since 2003 he is also a member of the Academy of

Engineering [AcTI] for which he organizes mini-symposia on architecture, on Smart Cities and on the Grand Challenges of the World. He retired as an active professor in 2015 and stays engaged in the national research & development master plan for the building industry in the Netherlands. a.c.j.m.eekhout@tudelft.nl / m.eekhout@ocatube.nl.

He started designers associations Delft Design and Boosting. In his free time he likes to sail. He likes to write articles in newspapers and international conferences, books and in future, maybe, a novel.

LIST OF BOOKS, WRITTEN OR EDITED BY MICK EEKHOUT

Architecture in Space Structures 1989, E, ISBN 90-6450-080-0
Product Development in Glass Structures 1991, E, ISBN 90 6450-111-4
Aluminium in Space Structures, E, ISBN 90-71642-13-5
NAi and Product Architecture, E, ISBN 90-5269-137-1
Architecture between Tradition and Technology, 1992, NL/E, ISBN 90-5269-113-4
Tubular Structures in Architecture, 1996, E,F,D,SP, NL, ISBN 90-75095-29-5
Stressed Glass, Zappi or Product Development for NAi, 1995, E, NAi Publishers, ISBN 90-72469-78-x
POPO, Proces Organisatie voor Product Ontwikkeling 1997, NL, ISBN 90-407-1631-5
Analysis, Design and Construction of Steel Space Frames, E, ISBN 0-7277-3014-2
Reflections on Building Technology 2004, E, ISBN 90-5269-265-3
Methodology for Product Development in Architecture 2008, E, DUP, ISBN 978-1-58603-965-3
Tubular Structures in Architecture 2011, E, Citect, ISBN 978-94-90675-01-1
Concept House DELFT Prototype, 2012, NL, TU Delft, ISBN
Componentontwerpen en productontwikkelen 2015, NL, IOS Press, ISBN 978-90-5199-538-1
Lectures on Innovation in Building Technology 2015, E, IOS Press, ISBN 978-1-61499-555-5
Delft Glass Design Innovations, 2015 E, IOS Press, ISBN 978-94-90674-04-5
Cobouw Columns van Mick Eekhout, 2015, NL, ISBN 978-94-90674-05-02
Lord of the Wings, 2015, E, IOS Press, ISBN 978-1-61499-549-4
Prototyping Maison d' Artiste, 2015 E, IOS Press, ISBN 978-94-90674-06-9
The Concept House Delft Prototype, 2015 E, IOS Press, ISBN 978-1-61499-551-7
The Delft Prototype Laboratory, 2015, E, IOS Press, ISBN 9781-61499-545-6
Bridges @ Leidschenveen NL, TU Delft, ISBN 90-5269-264-5
Delft Science in Design, 2005, TU Delft, ISBN 90-5269-327-7
Delft Science in Design 2, 2008, TU Delft, IOS Press, ISBN 978-1-58603-739-0
Glimpses of the Future, Boosting kijkt naar de toekomst, 2013, NL, Boosting, ISBN 978-94622-83527
Free Form Technology from Delft, E, 2015 E, IOS Press, ISBN 978-1-61499-553-1
Gieten en kneden, 2015, NL, IOS Press, ISBN 978-90-5199-540-4
The House as a Product, 2015, IOS Press, ISBN 978-1-61499-547-0
Glimpses of the Future, E, IOS Press, Amsterdam, 2015, ISBN 978-9-462-2835-7
www.mickeekhout.nl



Sieb Wichers [© Dana Mars]

Siebrandus or 'Sieb' Wichers [1976] is a complex façade specialist. Born in Dedemsvaart, a small farmers' village in the Netherlands, Wichers draws inspiration from nature and organic architecture. He obtained his Master of Science in Architecture [Honors] in 2003 from TU Delft, majoring in Building Technology. Since then, Wichers designed and rationalized some of the most iconic projects in the world.

The free form engineering of the Rabin Center project was not an unfamiliar territory for Wichers. Back then; he had just completed his award winning, free form graduation project the "Floating Fluid Pavilion", under the guidance of Prof. Dr. Mick Eekhout and Prof. Kas Oosterhuis. The organically shaped pavilion won Wichers the 1st prize and inventiveness prize of the Bouwen met Staal 2003 awards, the 1st prize at the AVB Buis in Beeld 2003 awards and a nomination for the Dutch Archiprix 2004.

It was at that time that Wichers started realizing the vision of his "archineer"; a vision influenced by his experimental studies on free form structures as a part of TU Delft first ever BLOB Group. Controlling the master model, the "archineer" is an interdisciplinary designer with thorough knowledge and passion for both designing and engineering with a cost-effective buildability point of view.

Wichers joined Octatube, where he was encouraged to implement his idea of 'archineering' into Octatube's projects. For the Rabin Center project, Wichers performed as a true archineer: juggling with designing, engineering, production, transportation and installation. First acting as the design engineer, he then supervised the productions in the Netherlands and in Israel and was finally deployed as the project leading site engineer until completion.

Wichers then joined Moshe Safdie's firm at Boston, USA. Working side by side with Mr. Safdie to develop the Marina Bay Sands – shaping Singapore's identity and becoming South East Asia's most iconic architectural masterpiece. Wichers played a pivotal role in designing the project's most complex parts, including two crystal pavilions, the podium's five bridges and canopies and other. However, his most significant contribution is the design of the lotus shaped Art Science Museum. For his efforts as a member of Safdie's team on this project, Wichers received the President's Design Award in 2011.

Wichers then continued to design and build another one of South East Asia's most celebrated landmarks: the Sports Hub. Together with Clive Lewis at Arup Sport, he designed the National Stadium – currently the largest dome in the world, as well as its moving roof and surrounding buildings of the hub. After completing the design alignment phase, he joined Hong Kong based Craft Façade, to manage the cladding's system designs and their construction of the award winning Sports Hub.

Wichers is also an entrepreneur, a writer and a founder of an international design firm, which is expected to be launched in 2015. sswichers@gmail.com