FREE FORM TECHNOLOGY FROM DELFT

Research in Architectural Engineering Series

ISSN 1873-6033 (print)
ISSN 1879-8225 (online)

Volume 14

Previously published in this series:

Volume 13. M. Eekhout and A. van Timmeren, Development and Realisation of the Concept House 'Delft' Prototype – An Example of a Collaborative Concept Development for Energy Positive Apartments

Volume 12. M. Eekhout and S. Wichers, Lord of the Wings – The Making of Free Form Architecture

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

FREE FORM TECHNOLOGY FROM DELFT

Prof. Dr. Mick Eekhout, editor
Chair of Product Development TU Delft

Co-writers: Mick Eekhout, Barbara van Gelder, Walter Lockefeer,
Martijn Veltkamp & Karel Vollers

FREE FORM TECHNOLOGY FROM DELFT

EDITOR Mick Eekhout
AUTHORS Mick Eekhout, Barbara van Gelder, Walter Lockefeer, Martijn Veltkamp and Karel Vollers
LAYOUT Manuela Schilberg, Saphira Jon, Octatube, Delft
MASTER DESIGN Sirene Ontwerpers, Rotterdam

ISBN 978-1-61499-553-1 (print)
ISBN 978-1-61499-554-8 (online)
DOI 10.3233/978-1-61499-554-8-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

Mick Eekhout (© Nadine Maas)

Free Form technology quickly became a R&D priority in academia and building industries when the first major projects had to be realized in Europe. Initially the applied technology had been poor, as CNC production didn't manage to catch up with the speedy development of 3D design programs that architects employed. Industry was hesitant to invest in this new field. Some Free Form buildings that in the new millennium got pushed onto the market, had shown serious defaults. Therefore many general contractors feared Free Form designs to turn into Free Form nightmares. Most of the first Free Form building proposals didn't get realized, like the Wilhelminapier, Rotterdam, of which the budget didn't suffice. The fish-like shaped construction designed by Gehry for the interior hall of the Deutsche Genossenschaft Bank in Berlin (Germany), did get built – at great financial loss. It caused Gartner, at the time the leading European façade manufacturer, to virtually go bankrupt and it pushed the take-over by Permasteelisa. The production industries didn't manage to materialize the proposed curved architectural shapes, so academics of the Chair of Product Development jumped in to jointly develop new technologies.

As knowledge and experience grew, the results improved. The Rabin Center in Haifa (Israel), showcased a successful technical development, but commercially at a great loss. Others as the Municipal pavilion at the Floriade, Hoofddorp (NL), the town Hall of Alphen (NL) and the Malmö Green House (Finland) were successful, both technically and financially.

Dr. Karel Vollers, after publishing his acclaimed dissertation Twist & Build, headed the Chair's Free Form technology (aka Blob technology) group projects from 2001 – 2011.

The research group consisted of PhD students (Martijn Veltkamp, Walter Lockefeer and Barbara van Gelder) and approx. 50 BSc and MSc students. Mick Eekhout and engineers of his firm Octatube, had great impact by contributing their Free Form technology experience.

In a decade, knowledge of Free Form technologies spread all over the faculty. Simultaneously, in the research portfolio of the Chair of Product Development, sustainability issues became more important. In 2011, after a R&D portfolio re-arrangement, only the PhD students were left, to continue their projects. The research group was dissolved and with the retirement of prof. Mick Eekhout, the Chair as a whole got terminated.

The Free Form technology group's body of knowledge now is integrated into the section Architectural Engineering. And professor Kas Oosterhuis continues his 'from-file-to-factory' work approach in his Hyperbody group [www.hyperbody.nl]. Many inspired findings of the Chair of Product Development's Free Form group are assembled in this book. Additionally the book contains an extensive article taken from Lord of the Wings, written by Mick Eekhout and Sieb Wichers, on the development of the sandwich shell roofs for the Rabin Center, [Reference IOS Press, Amsterdam, 2015, ISBN 9781614995494]. This selection of articles represents our technological contribution to Free Form Architecture.

Mick Eekhout

Karel Vollers

This page intentionally left blank

This page intentionally left blank

CONTENTS

INTRODUCTION

'Free Form Design' has enjoyed increasing popularity in the recent 'zero' decade. Around the turn of the millennium architects discovered sophisticated computer programs with which they were able to design volumes out of the classical vocabulary of the Carthesian grid. Building volumes that they could deform, stretch and manipulate as it were in rubber.

The success of the Guggenheim Museum in Bilbao, designed and engineered by Frank O. Gehry and inaugurated in 1997, opened the eyes of the world to the plastic possibilities of Free Form Design. That is, on the side of architects and their admiring clients. Some architects draw up complicated but surprising and attractive Free Form Designs and win design competitions. The next step towards realization is to involve the making industry and the contractors with realising these dreams. They discover that the art of Free Form Designing is a chewing gum invention by the digital designers using standardised design programmes once developed for Hollywood films. These films were virtual realities and did not have to be built. But architecture has to be built in order to be appreciated above the level of the competition scheme. So the thinking about realising Free Form Technology had to start. In the beginning there was no experience and not even a motivation on the making side to join in. The Guggenheim has been built with very traditional materials and methods. But after more designs the desire and logic for an adapted Free Form Technology became apparent. In the practice of Mick Eekhout (in his 'design & build' company Octatube Delft) the first experiences with Free Form Designs failed, were aborted, were a disaster or led to unfortunate events as bankruptcy of competing firms who took the projects without major Free Form Design experience. One could learn many lessons from these early experiments. This is the main reason why these experiences are shared with the reader in this book.

But they also introduced at the Faculty of Architecture of TU Delft around the turn of the millennium the necessity of developing a special Free Form Technology. Developments at the TU Delft were directed towards the topic of architectonical Free Form Designs from the demand side including the contextual considerations and the Blob Technology to be developed from the scientific supply side, including the production, material design and processing aspects.

At the Department of Building Technology a group of Blob Technology Research was installed in 2001 after the successful (cum laude) dissertation of Dr. Karel Vollers and amidst a number of practical Blob realizations in the Netherlands and abroad by the laboratory cum company of Mick Eekhout. Karel Vollers was appointed as the leader of the Blob group. The group initially worked with Master students in their graduation year, scouting the numerous possibilities in design and technology.

In the official Research Assessment of April 2004 on the period 1997 to 2002 the Blobs/ ICT program received a high appraisal as a research program. For Quality 4, Productivity 4 relevance 4 and Viability 4 the Blobs program received in fact the highest appraisal of all programs at the faculty of Architecture. This mood was continued under the research nestorship of Mick Eekhout. Enthusiastic colloquia were organised in February 2008 in which all researchers showed their work in pitches and provoked debates. In May 2008 the Mid Term Review was organised with a good outcome for the Blobs program. A change of policy came in March 2009 when the dean, after a dispute on a minor subject, dismissed all research nestors. The programs were regrouped and in 2008 there was a mid term review, in autumn 2009 a faculty review was organized and finally an official Research Assessment in 2010 over the period from 2003-2009. The Blob research group was now a part of Green Building Innovation. GBI received the highest awards of all faculty programs.

During these successes explosions of research initiatives followed, amongst others because of the positive and enthusiastic spirit of the Blob/ICT researchers, an improved financial situation at TU Delft and efficient secretarial supervision. The number of PhD students quadrupled in the department and in 2007 there were some 20 researchers in total in the Blob program and some 80 researchers in the department as a whole, amongst whom 50 PhD students and 30 staff plus external PhD students. The research at the Department of Building Technology, monitored by research nestor Mick Eekhout was divided in 5 programs: 'Blobs', 'Industrial Building', 'Informatics', 'Zappi' and 'Climate Design', which partly overlapped and influenced each other.

In the enthusiastic exploration of new research initiatives PhD students were sent to worldwide conferences. After the IASS Conference in Monpellier 2005 the initiative was taken to install a sub-working group of the IASS on Free Form Design, acknowledging that Free Form Design is a topic to be closely studied in the short future as architects are urging for realistic and affordable answers from the technology side. In September 2006 the first International Free Form Design Colloquium was held in Delft, where a number of the world players on this field were invited. Alas this colloquium was not recorded in a booklet. The IASS conference of December 2008 and the Valencia IASS conference in September 2009 witnesses the technological problems related to the design, engineering, production and building of Free Form structures and buildings.

In the mean time a changing strategy has governed the research activities at the faculty of Architecture. After the 7 rich years the 7 poor years were announced. Thanks to the maintaining of a rather strict hiring and firing system of temporary researchers the balance sheet of the faculty is kept in a sort of neutrality. As a result of this the chair of Product development was reduced in 2009 from 6,4 fte to 1,4 fte. The core of the Blobs work has to take place in other institutions and the glorious time of Blobs from Delft had to be documented for the world and for history. This was the main reason of composing this book. Dissemination of (new) knowledge is, after all, one of the tasks of academia. The Blobs research group is happy to have laid the first foundations of this field of expertise, which from conceptual architectural design, through the CAD/CAM engineering and development of new Blob technologies and their first prototype production applications will demand much investment and energy yet. It is a known fact that, if this research is not executed cautiously and its results are implemented in practice, the effect of realising

Free Form Designs will be disastrous for many companies who do not rely on the results of research and development. In the past Free Form Designs made by architects have caused many victims, both on the client side, the architects side, the engineering side, the producers side and the contractors side. Hence amongst builders the popular nickname 'Free Form Nightmares'. But this is a phenomenon that encompasses new developments all the time. This is the reason why the practical Blobs projects are monitored and analysed to gain both practical and theoretical momentum.

Special attention has been given in this book to the processes of experimenting with prototypes, which, certainly in a pioneering field, can be a very fruitful field of academic research. For that reason the Chair of Product Development is fortunate enough to know a strong bond with Octatube Delft, the design & build company of Prof. Eekhout. Without mixing the advantages and disadvantages of having two hats on, this collaboration results in a merger of theory and practice. It also results in realising experimental prototype projects which would b not have been possible without this merger of academia & industry. Prof. Eekhout regards Octatube as his laboratory for experimental innovations and his worldwide projects as his portfolio on which he philosophises in academic publications, just as these. Dr. Karel Vollers has a similar relationship with external companies as Van Tetteroo Glas and Alcoa in Harderwijk.

This book has been edited from publications of members of the Blobs Research Group to mark the end of the current Research Assessment period from 2001-2011. This collection of representative publications and articles of the recent and current research of the Blobs program has been brought together to mark the momentum and to extend the contact with other Free Form designers and researchers. The contents of this book 'Free Form Technology from Delft' is as follows. In the introduction the overall situation of research at the department of Building Technology is explained in general overviews.

In the subsequent contributions a number of chapters and paragraphs describe the findings, publications and philosophies on designs, developments research and experiments by prof.dr.Mick Eekhout, dr. Karel Vollers, Barbara van Gelder and Walter Lockefeer. They will reveal that our research connects to both a material side as well as an immaterial side. On the immaterial side the reader will find philosophies on Free Form design, why it is made, how it is done, what are the secrets of designing in Free Form to impress the clients and the public audiences. Then the engineering and material experiments are described. They have taken place in two fields: the development of Free Form components, in aluminium, reinforced concrete and also in glass. These developments end for example in a re-usable moulding machine for production of Free Form glass panels by Karel Vollers. Other material experiments concern metal structures, glass façades and glass fibre reinforced roofs. All of these research and development activities stem from larger or smaller material experiments, resulting in small scale prototypes or in real scale prototypes for project buildings, in many cases around the world.

A concluding essay on the complexity of Free Form Design realisations and how to best collaborate with the different parties, closes off the content. At the end the epilogue gives a view on the future of the results and further work on Free Form Technology.

At Delft two other groups of researchers and designers are active on the field of Free Form Design: prof. Sevil Sariyildiz (Design Informatics) with PhD students working on the informatics side of Free Form Design and prof. Kas Oosterhuis in his 'Hyperbody' Research Group on the basis of a starting grant from the dean. Between the researchers of the three chairs (including the chair of Product Development) there are several collaborations. All three chairs are now part of the department of Building Technology, to be called Architectural Engineering in future. It seems inevitable that the three chairs join forces in a collective research program. That is not yet the case.

The long term future is the situation in the future research programming which arises after the restart of the 3TU.Building Research programming. This programming could take over the subject in a broader context, continue the entire Dutch Blob Research Group and put this research into a context of societal needs. One of the future aims is to reinforce our research with the respective chair research of our colleagues at the universities of Eindhoven and Twente. Hence three future steps will be taken to reinforce the research programs:

- To add complementary researchers from friendly chairs in the department of Architectural Engineering at TU Delft;
- To enter into collaboration of Free Form Design research between the faculties of Architecture, Industrial Design Engineering, Mechanical and Maritime Engineering and Aeronautics at TU Delft;
- To enter into a synergetic collaboration within all building-related faculties in the Netherlands (TU Delft: faculties of Architecture, Civil Engineering, Technology, Policy & Management and Architecture at TU Eindhoven and CTW in Twente) in a new '3TU.Building Research Centre with yet unknown set of programs, aimed at validation by society and the building industry.

Prof.dr. Mick Eekhout,
Chair of Product Development,
Faculty of Architecture, TU Delft

01 PAST AND FUTURE OF FREE FORM DESIGN

Mick Eekhout

1.01 INTRODUCTION

Prof. Massimo Majowiecki of the university of Bologna challenged me at the occasion of the IASS conference in December 2007 for a consideration on the seriousness of Free Form Designs for the future. What about the possibility of Free Form Design being a new architectural language, an architectural style even, or do we see only a range of out of scale one-off object designs? How deep will the influence of Free Form Design go? Will the challenges in formally juggling with Free Form Design darken the functionalist design of the 20*th* century? Will Free Form Design menace 80 year old Functionalist Design at last after the sieges of Post-Modernism and Deconstructivism have been endured? How far will the influence of digital design reach in the lives of the younger generations and what will be the effects on the expression of that generation in Free Form Buildings?

FIG. 01 Valencia Oceanografic, Felix Candela

1.02 CHALLENGE

From the times of the pioneers all through the 1960s and 1970s the focus had been on the economic pursuit of load bearing structures with minimal material. In due time this mixture required intensive labour growing more expensive over the years, both in design and engineering as well as in productions off-site and building on-site. In the gradual change of decreasing material costs versus increasing labour costs and the increasing economies of Western Europe the total costs of space structures became uninteresting for economic architecture. However, the economy boomed.

The focus came on the design as a token of intellectual progress. Architects started to invent their own space structures for specific projects, combined with intelligent spatial schemes, which could be recognized as the High Tech Structures of the 1980s. In the 1990s regular space frames were mostly substituted by project-designed spatial structures, revealing the intelligence or genius of the project designers: mostly the architect and his duo partner the structural engineer. In their collaboration was a balance in specialization and mutual respect The Centre Pompidou, Paris, of 1976 by Renzo Piano and Richard Rogers introduced the High Tech Architecture era, which was formed for a large part by the British High Tech architects and many local followers. It pronounced intelligent technology in structural design in well-balanced buildings.

FIG. 02 Space structures (Air India hangar in Dubai during construction)

FIG. 03 Centre Pompidou: had to make a change in fashion in architecture

One decade ago the first serious Free Form Building was designed and realized: The Guggenheim Museum of Frank O. Gehry in Bilbao (1997). Although architecture critics on the work of Gehry could have expected this type of building, its extreme contrast in form and prominent location just outside the 19th and 20th century city of Bilbao shook the world of Architecture.

FIG. 04 Guggenheim Museum in Bilbao with an external message and an internal mess

Bilbao's Guggenheim Museum landed as a outer space craft aside of a rather dull European town. The very contrast between this bold design and the buildings in the existing city was crushing. Even adjacent buildings still under construction were old-fashioned by centuries. Although connoisseurs of Gehry's work could have expected this, it was the close proximity in an ordinary European city that made the confrontation. Its Free Form Design also made a change in the world of Structural Design. Architect Gehry has a characteristic way of working: he models in clay, paper and cardboard on model scale.

This model is scanned and digitalized in perfection and taken as the base design on which the entire computer aided engineering, manufacturing and building is based. Gehry ideally forces his subcontractors also to work in the computer program Catia. Being the first grand Free Form Design in Europe, this American design realized in the Spanish building tradition and no doubt Spanish pricing still had an imbalance of architecture and technology. Nevertheless it pointed out the direction to pursue it. This new and sculptural Free Form Design architectural vocabulary was not realised by a technology with equal intellectual and progressive stature. The steel structure had its own logic, but not an aesthetic appeal. It was heavily 'under designed'.

The gap between architectural design and realization technology had been widened by the enthusiasm the perfection of the Catia design programs generated in Gehry's engineering department. The Spanish builders did not have the same tools, nor the time to prepare themselves on a similar level of perfection in execution. Their technology lagged behind architectural design. The architect was more far-sighted than the engineers and contractors. The steel structures behind the facades were blunt and simple. They were hidden behind the cladding. So who cares? An immense gap between perfect architectural digital design and material realization had to be bridged.

In the last decade a number of Dutch Free Form buildings have been realized that indicated the same gap between design and realization. Many lessons were learned considering the collaborations in the entire building process; from design to realizations. The initial shock reaction of 'Free Form Nightmare' among technologists and contractors faded away. The eagerness of young architects to explicitly print their names on the objects overshadowed all necessary extra attention for the engineering, production and realization process of these complicated Free Form Buildings. An ego-driven change in fashion, with many uncared aspects in the later process. Only seldom these Free Form Designs were realized in a completely mastered and balanced process from initial idea to the very completion. At TU Delft a small research group 'Blobs Research' was established in 2001 to narrow this gap in production and realization technology. The lessons learned are addressed to the audience by the different lectures from the Blobs research group in the conference and are incorporated in this very consideration. For the first time in the almost 60 years of existence of IASS the balance between Structural Design and Architecture has definitely changed to Architecture dictating Structural Design in case of Free Form Buildings. So gradually a producer's dominated technology called 'Shell Structures' has been substituted first by a producer/consumer balanced technology called 'High Tech Structures' and at last by a consumer induced technology called 'Free Form Structures'.

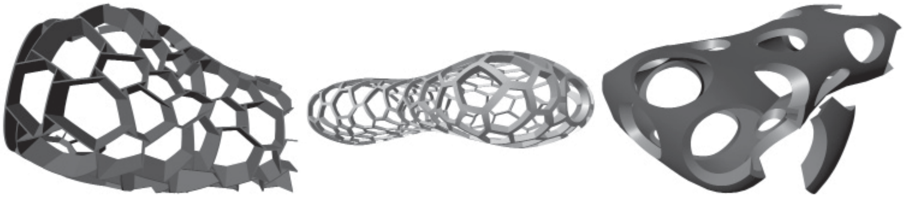


FIG. 05 Typical work of the Delft Blobs research group: Martijn Veltkamp

1.03 INITIATING TECHNOLOGICAL IMPULSES

Space frames have been realized from the 1970s onwards aided by –for that time- advanced computer programs. These were Finite Element Methods for analysis of forces and deflections in a space frame under external loading. The programs used punch cards: every command every sentence one card. There were no means of graphical check. Yet in the practice of Mick Eekhout the most complicated space frames were analysed: one time (1978) with over 5000 nodes, using IBM's highest night priority. It ran the whole night and did cost a huge sum of money. This program has been outdated for at least 30 years. The very existence of the FEM programs boosted space frames in architecture. Space frames could not have come into existence without the FEM programs.

The current FEM programs like SAP 90 are refinements of the earlier programs, they are connected with graphical programs, they are being processed on personal computers rather than on main frames, they calculate in real time and they are so fast that they can display graphically the deformations in exaggerated sizes for a proper interpretation and understanding by the engineer. The FEM programs are incorporated in the CAD/CAE/CAM/ CAB range, assisting the complete engineering of load bearing metal structures. Space frames are still interesting for large spans. But in the Western world architects would favour to design a project based structural system now and have their engineers engineer this before tendering, rather than lay the design and engineering in the hands of specialist producers after tendering. In recent decades there was a shift in power from the specialist producers to the project architects and engineers, parallel to the consumer's market: a shift from producer to consumer. This had everything to do with the growing economy in western countries, to the level of a luxurious market. No need to save on tonnes of steel as long as the expression is the desired one. The famous 'Birds Nest' stadium of Beijing used eight times the amount of steel compared to average stadiums of the same size.

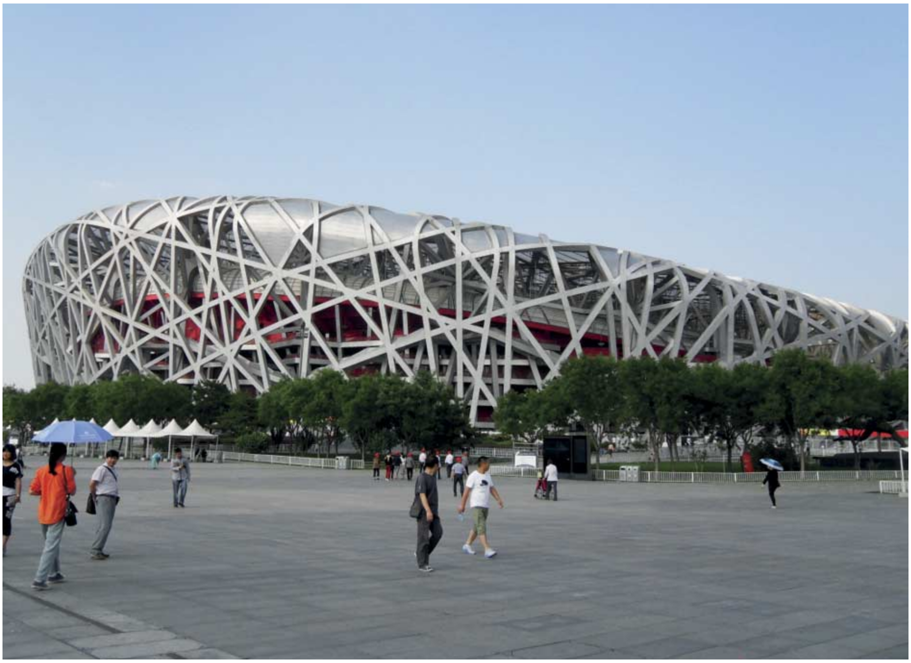


FIG. 06 Olympic Stadium Beijing, Herzog & DeMeuron

This seems a development similar to the theory of clinical psychologist Abraham Maslow (1908-1970): as described in the famous Maslow's pyramid, published in 1943 in 'A Theory of Human Behaviour' [Ref. 01.01]. An individual develops himself going from the primary biological needs to the needs at the top of the pyramid of self-actualisation. As this is valid for an individual, it is also valid for a group of individuals, say architects as the leading party in the design process.

Something similar could be worked out concerning the position of a building project in the economy. Buildings in Western societies still fulfil the basic needs for sheltering houses. More and more the stairs to self-esteem and self-actualisation initiate design contracts where the design manifests more pretence than bluntly housing people: these people have to feel safe, they need an environment in health and moral. The next level cares for the more intimate needs of friendship, family and intimacy. This was the philosophical focus of the 'structuralism' generation of Herman Hertzberger and Aldo van Eijck. They were the champions of architecture based on human needs in social context of living communities.

After that socializing generation of architects a next generation came with a higher level of recognition and esteem: they wanted to be valued as a new generation. At the age of 34, Renzo Piano together with Richard Rogers started to design their entry for the Pompidou Centre and invented their architecture of the inside out structures. As Piano admitted in a general discussion at the LSA conference in Sydney in 1986: "We wanted to change fashion in architecture” [Ref. 01.02]. And Pompidou did change architecture! It was a bold statement of a new generation of architects. And many contemporary architects followed.

As a set, architects of a new generation, wanting to show their new footprint, have to win design competitions in order to gain their target. They have to be allowed by older jurors, recognizing rising quality in the competition design and wanting to give new visions a chance. The new generation could manifest its awareness by initiating a new architectural language based on axioms they favour. Basically it is a generation fighting its way into the architectural scene. Each new generation can initiate a new language in architecture by selecting as the new generation a new vocabulary, new means of communication, a new vision and a new material expression.

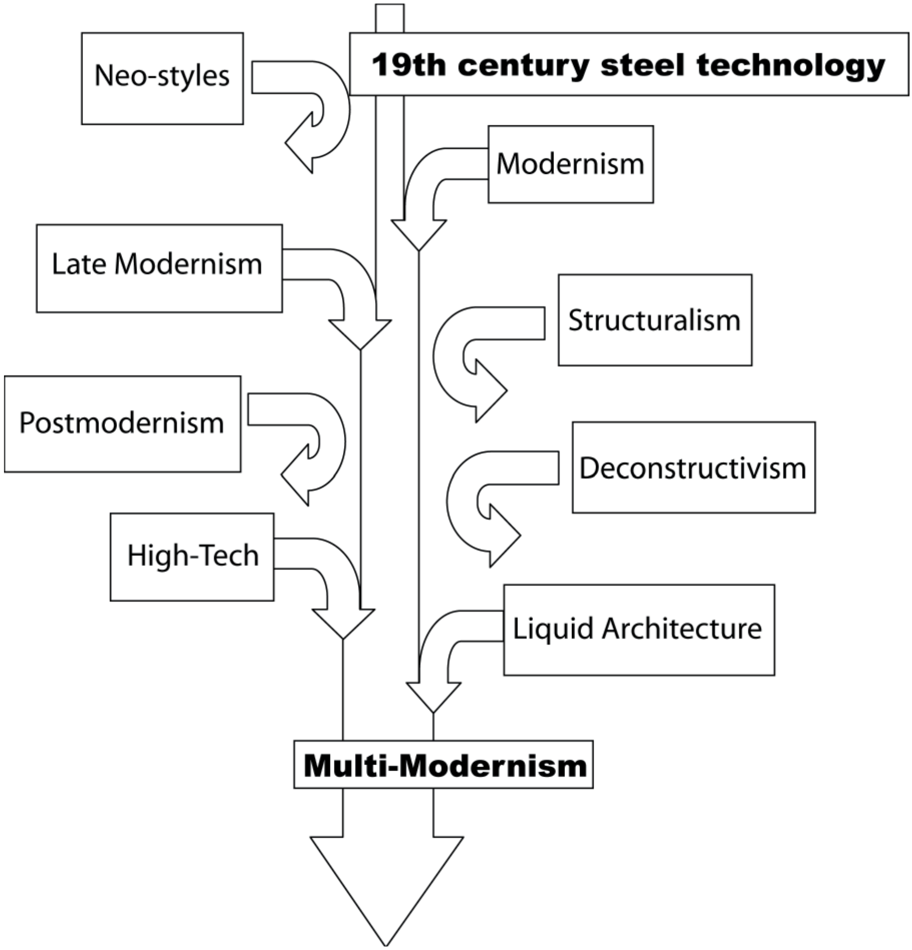


FIG. 07 Overview over ‘isms’ in architecture in the last century

Free Form Design is greatly initiated thanks to available computer design and engineering programs, derivates from the cartoon movie industry. This is a technical injection. On much the same way the Dutch 'De Stijl' movement of the 1920s and the International Modernism movement after that was greatly stimulated by two technical developments. The first was the development of reinforced concrete slabs and walls which could be stacked together or cast together to form horizontal cantilevering floor or roof planes and would lead to much more of an horizontal expression than the traditional vertical expression in architectural façades. The second one was the development of bituminous roofing, by means of which (almost) flat roof surfaces could be made, even in rainy climates. These two development stimulated very much 'thinking out of the box' and led to for example the much admired 'Maison d'Artiste' as designed by Theo van Doesburg en Cor van Eesteren in 1923. These technical developments stimulated a new architectural approach, that later was recognized as a new architectural style. It is not us, technicians, to proclaim that Free Form Design will lead to a new architectural style and we would leave this to architecture historians. At this moment in time one could only conclude that Free Form Design, in its turn accelerated by new computer programs, leads to new technology and a new, forced way of building process collaboration to accomplish these complex Free Form buildings. Recognition as Free Form Design as a technological fashion or obsession, rather than an architectural style, is to be defined by architectural historians in the decade to come.

FIG. 08 Prototype of Maison d'Artise 1923, realized at TU Delft 2003 by students, but originally one of the first designs of a new architectural style, boosted by the technical developments of reinforced concrete floor slabs and watertight bituminous roofing in the 1920s

1.04 THE FIRST FREE FORM DESIGNS

Post-Modernism was based on philosophical axioms. It opposed the functionalist society with reasons and positioned itself as an opposition of that mode of living. In architecture it would be soon called a style, much more than a fashion. Post-modernism had a sometimes angry, sometime humorous relationship with Modernism. Gehry was a Post-modernist in a part of his career.

Deconstructivism is another style of architecture departing from the many facets of society. Deconstruction was started by the French philosopher Jacques Derrida. Construction and Deconstruction both give an entry for logic and ration. Truth always has more ways of approach. The first manifestation was believed to be the design competition for La Villette Parc in 1982 (Tschumi). Many of the earlier Deconstructivist architects, trying to make non-functional and astonishing objects like Peter Eisenman, Frank Gehry, Bernard Tschumi, Daniel Libeskind, Zaha Hadid, Rem Koolhaas and Coop Himmelb(l)au and brought together in an exhibition at New York's Museum of Modern Art (Moma) in 1988 have denounced to be a member of any Deconstructivist stream, have developed themselves further and are using very sophisticated computer programs.

FIG. 09 Deconstructivist Design, Parc Lavilette, Paris by architect Bernard Tschumi

Most of them have designed Free Form buildings with the aid of powerful design programs. After they later were called 'Free Form Design 'or 'Blob' architects, not a single architect wanted to be put in a group he did not invent himself. Their ego's are too big for a class. The transition from Deconstructivist Architecture to Free Form Architecture has not so much to do with a new philosophy, but rather with the availability of technical computer programs with increased power and more accessibility, simplified and adapted from film making to architecture.

A number of Free Form Designs have been made in the Netherlands from 2000 onwards. A pop music theatre in Breda and a town hall in Alphen aan den Rijn designed by Erick van Eegeraat, a hotel extension in Almere by architect Will Alsop and two pavilions on the 2002 Floriade in Hoofddorp designed respectively by Kas Oosterhuis and Asymptote Architects from New York. The designs were brilliant, but an adequate Free Form technology lacked in all cases. Either new technology had to be developed for the project at hand, or the architects decided to employ traditional handicraft techniques. The only Blob design that was consequently developed into a new technology was the Rabin Center in Tel Aviv, designed by Moshe Safdie, followed by a Dutch technological process of re-design, development and research engineering, production, assembly and installation.

FIG. 10 Pop podium, Breda; Erick van Eegeraat

FIG. 11 Town Hall, Alphen; Erick van Eegeraat

FIG. 12 Provincial Pavilion Floriade 2002, Hoofddorp; Kas Oosterhuis

FIG. 13 Bus Halt, Hoofddorp; Maurice Mio

FIG. 14 Municipal Pavilion Floriade 2002, Hoofddorp; Asymptote Architects

FIG. 15 Theatre Almere, Will Alsop

FIG. 16 Rabin Center in Tel Aviv: Dutch re-design, development and research, Moshe Safdie

1.05 FREE FORM DESIGN AND SUSTAINABILITY

An extra complication in Free Form Design processes is formed by the considerations of sustainability. How is the building re-usable as a building? How is the building re-usable in components and is there any profit to be gained in re-using the materials coming from the Free Form building? These are questions running parallel with the questions one could pose to all new buildings. In the short future we will have to develop buildings that do not consume energy, but are energy-neutral or even could produce energy. European politics will lead within 10 years to a prohibition of energy consuming new buildings. In this aspect Free From buildings are comparable with all other new buildings. The choice of its constituent materials should be directed towards sustainability, both in the making as well as in the maintenance of the building. Re-using the building after a first generation of service is best organised at the level of the building itself. It does not seem very practical to re-use one-off components: the particular form of the components will never fit into any other building. And to strip the complete building at a level of materials and to pulverize the materials as this is done in asphalt tops of roads, does not make sense as only 3% of the value of the building is left.

FIG. 17 Pulverizing a decent building should be avoided: capital investments go from 100% to 3%. The gravel is used for making-concrete again

The architect and the entire building team just have to develop buildings that are spacious enough to be adapted to other functions in a next generation of use and of which the material choice is so durable that in would endure more than two subsequent generations (20/30 years each) even with a change of users in between. In this aspect Free Form Buildings are not different from orthogonal buildings.

01.06 CONCLUSIONS FOR THE FREE FORM FUTURE

Free Form Design is a direction in Modernist Architecture that is inspired by the countless possibilities of digital design computer programs, where the architect / designer can freely form a spatial envelope around a building as a sculptor, keeping the restraints of production and erection and of complex processing in mind. Free Form Designs are almost impossible to re-use in another form: the final form developed by the architect cum suis has to be 'classical' (quality) to be seen as a new monument. At the same time in future sense it has to be spacious (quantity) enough that sustainability is only employed in the re-use of the building by other functions. The ethics of Free Form Design do not prevent designers to win competitions with these designs as long as they are knowledgeable on the production and realization side of the design and as long as the clients are prepared to pay the extra costs compared with average projects. The Free Form Design process is usually much more complicated as the geometry is making the dialogue between the different building team partners even more complex. A direct collaboration between designers and producers to realize the Free Form Design in components, is unavoidable for a sound development of Free Form Architecture. Without this it will frustrate many in the process and may lead to a temporary and short hype. When production technologies and computer aided engineering, production & building is pursued, the current experimentation price level will be reduced, although still higher than traditional orthogonal buildings.

01.07 REFERENCES

REF. 01.01 Maslow, A., Toward a Psychology of Being, Wiley, 1998

REF. 01.02 Piano, Renzo, quote during a speech at the LSD conference, Sydney, 1986, written down by Mick Eekhout

02 TWO FAILED PROPOSALS: GALLERIA ROTTERDAM AND DG BANK BERLIN

Mick Eekhout

02.01 GALLERIA METRO STATION IN ROTTERDAM, 1995

The first of the Dutch Blob buildings was a design of architects Zwarts and Jansma for a railway station crossing a tramway in Rotterdam-South: the Wilhelmina-pier. The design of the main structure contained steel trees with thicker and thinner branches in varying heights. The tips of the top branches were covered with a triangulated glass roof, in a hilly, undulating form. The architects and the engineers ABT had thought of a nodal system to suit the many different corners in which the glass panels had to be fixed. ABT was smart enough to have several talks with national and international specialist-companies to check the validity of the design and the price level. The international parties declined. We made a material proposal for an alternative node which would enable the steel riggers to accurately position the tops of the steel top rods supporting the glass nodes. The secret was the surveying of the exact location of the centre lines of the corners of the triangular glass panels. For all components of the roof: both steel and glass are produced simultaneously in different factories and from theoretical drawings. The silicone seams between the glass panels are 10 to 15 mm at the most. Rejection already happens when there are larger differences in seam widths than 2-3 mm. That was thought to be the (wizardry) domain of the glass subcontractor. We had thought out a logistic 'modus operandi', which led to continuous 3D surveying of all installed components, adjusting them to the exact required level and X,Y,Z position. With these components we drafted our price and were very astonished that we were the lowest bidder at 12 million guilders. Alas, the architect and engineers had grossly underestimated the complexity of the design realisation, despite the warnings that had sounded from the pre-talks. The budget appeared to be only 4 million guilders! The architects and engineers were dismissed and architect Cees Dam designed a flat sloped glass roof which met the budget but was not worth publishing here.

Despite the initially cautious approach, a beautifully designed, but experimental and highly complicated structure with a customised glass construction on top was aborted. The architect and engineers were extremely disappointed. Their publications witness this. [Zwarts et al. 2003, Nijsse 2003]. Only years later one recognizes that this elegant but technically extremely difficult roof deserved a pre-engineering contract with a specialist-contractor, a real size mock up and a budget adapted to the stature of 'Liquid Designs'. The allowed budget was not even enough for a standard space frame and straightforward frameless glazing. But the relationship between the tendering parties was not that open that the architects wanted to persuade the client to enter into a co-design collaboration. An understandable, but fatal mistake which did not bring the first of the Dutch Blob designs to life, even before the name was established. It was 8 years later that in Warschau the roof over the Zloty Terasy was built (architect Jon Jerde Design) in much the same form. So the architects were simply 8 years too early in time and had not allowed the Dutch building industry to get accustomed to this high degree of complexity before the tendering process.

(Reference to figure 123 of this book: Structural set-up with steel tubular trees, covered by triangulated laminated glass panels, Galleria Rotterdam.)

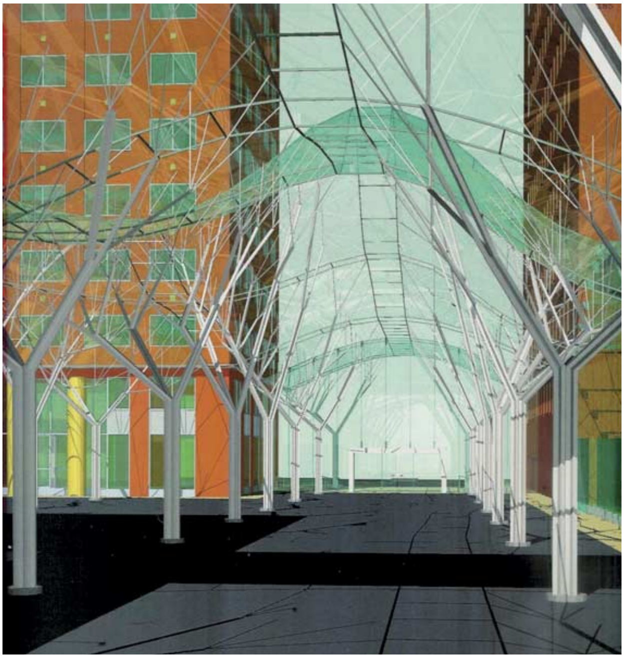


FIG. 18 Galleria Wilhelminahof, Rotterdam

02.02 DG BANK BERLIN, 1996

State-of-the-art computer programs enable architects to produce Free Form Designs for buildings. In contrast with orthogonal architecture Free Form envelopes are not easy to develop. Among the bodies that can be developed the old-fashioned way, cones, cylinders and spheres are counted. They are, in our current view, highly regular bodies. But in the last century they were viewed as highly irregular bodies and were introduced on top of the century old domes and cylinders: saddle-shaped hypar (in full: 'hyperbolic parabaloidal') surfaces, as these were easily to be calculated and realised by hand. They were governed by straight rules and hence moulding surfaces were not hard to build by specialised concrete carpenters. The world master in this field before computers was the Spanish Mexican Felix Candela (1910-1999), who took the Spanish technology of reinforced concrete shells as developed by Eduardo Torroja (1899-1961) at the time of the Spanish Civil War (1936-1939) and fled to Mexico, where he designed and built his master pieces. Usually they were extremely thin (50 mm) reinforced concrete shells made in an on-site timber mould. His mathematical and mechanical knowledge and insight assisted him to realise extremely thin concrete structures. After he had collaborated with space frame expert Castano (Triodetic space frame systems) on the roof of the main stadium at the 1968 Olympic Games in Mexico, he withdrew from the building industry and went to live on an island in Greece. The ratio between labour costs and material costs had changed, also in Mexico; his structures needed little material and lots of labour. Candela realised beautiful shells as big, extremely thin cantilevering roofs. His Chapel of San Vincente de Paul in Monterry is very elegant. The pioneer came and started a generation of buildings. With his retirement the shell era seemed to have vanished.

His works were, as it were, continued by Julius Natterer in Germany/Switzerland and Heinz Isler in Switzerland. They focussed on efficient mouldings and timber shell structures respectively. Isler passed away, while Natterer was the timber professor and known for his 'Holzbau Atlas', that was translated into Dutch in the 70s. Also ABT (Pestman and Oosterhoff) built timber hypar shell structures in the 60s. Not long after that the prices of mould carpenting these became too high. The joint forces of economy and architecture killed the interest in shells. How come fluid design architecture with its extremely high geometrical complexity, more even than the 20th century shell structures, came into the spotlights 5 years ago?

02.03 THE GUGGENHEIM MUSEUM BILBAO, FRANK O. GEHRY

In 1998 I was asked to give a series of lectures in Spain after the publication of my book 'Las Structuras Tubulares en la Arquitectura' [title of the English version: 'Tubular Structures in Architecture' ISBN 90-75095-29-5, Ref. 02.01] The tour brought me to Seville, Barcelona, Valencia, Madrid, Vigo and Bilbao. Just after landing and before lecture time I went to visit the Guggenheim Museum. After seeing it and impressed by this architectural bomb, I dramatically changed the slide show by drawing mini pictures on translucent paper for the slides. Yes, it had been realised in Spanish technology, but the signature of the master had not been tampered with. The building was a sculpture! It was a building so interesting sculpturally and spatially dominant that the museum needed no sculptures to draw visitors. Overshooting? Of course! A museum should house art and should accommodate it modestly, abstractly and neutrally. This building was brutality! But the building was also one of the first Free Form Design buildings of the last decade. The town of Bilbao never was the same after Gehry. The mayor was right. This museum, even more than hosting art, was a sign of a brand new architecture; it was also a true cultural deed and a social manifestation. A visual bomb had been planted on the river bank. This 19th century town all of a sudden became middle aged. Even the congress building, under construction down the river, had the looks of a sixties building hopelessly out of date, even before it was completed. The form of the building was extremely expressive, a flowering explosion. One could detract from the Spanish mode of building: rude and with blunt details, making it far from perfect. But Gehry's first European building loosened the tongues. Up to Tel Aviv, I noticed, it was the talk of the day. Architects were jealous of the first use of titanium panels, probably acquired via the Russian new business channels from one of the previous Soviet republics, one said. They could only afford aluminium panels.

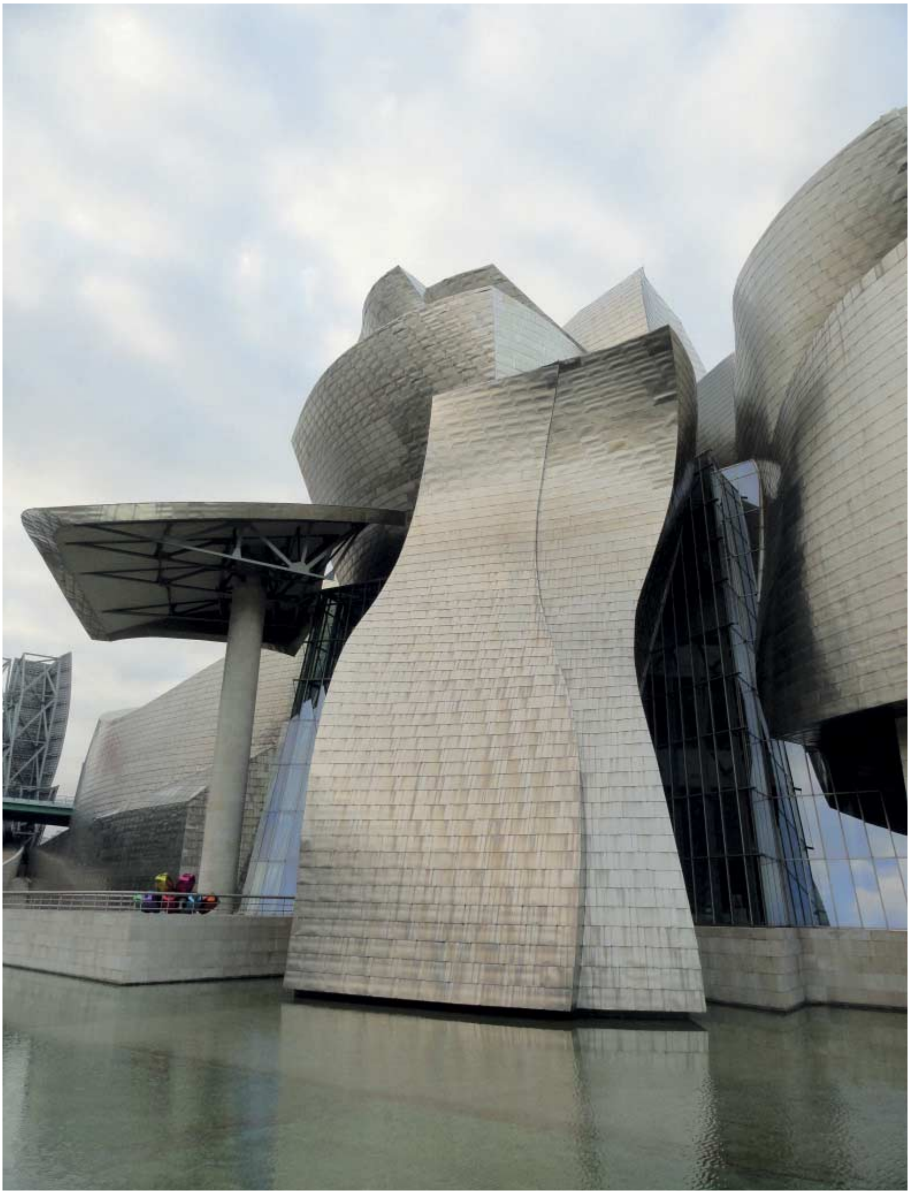


FIG. 19 Guggenheim Bilbao, Frank Gehry

FIG. 20 Messe Leipzig. architect Gerkan, Marg und Partner

Octatube has realised a number of building parts in Germany in the 1990s. In 1990 we were the first who dared to load glass in a structural way (Glass music hall, Amsterdam). First in the Netherlands and after a few years building structural glass also was realised in Germany. This was much to the liking of enterprising German façade advisors like Klaus Glas (Wiesbaden) and Petar Reich (Frankfurt). Glas was hired to prepare the Messe building in Leipzig in 1996-97, for which I proposed him a connection detail of a sloped glass sun louver panel and a steel tensile rod perforating through this glass panel. The building in Leipzig was much too big for us. The cylindrical building was to be build by Seele and Mero, our main German competitors.

During one of the discussions at that time, Klaus asked my opinion of Gehry's new design in Berlin. And he showed me the design drawings. Interesting and difficult, extremely difficult. Really something one allows for his best competitor. Let him bite the bullet. But at the same time it seemed a challenge due to that complexity. I gave a price indication on the spot, based on the dimensions he mentioned: 9 million Guilders, eh D-Mark. He said: "No Mick, better study this original in more depth. May be you will find alternatives, which will make it more economical. Take care, don't burn your fingers". He did not have to tell me twice. In Delft we sat round the table and also my engineers were very impressed by the complexity of the design and by the individual character of the elements and components. It looked like clock makers work. You have to be in Switzerland for this type of accuracy. But back in Delft the opportunity seemed too challenging to let it pass by. So I said one week after the previous discussion with Klaus that an eventual alternative would be based on my space frame system Tuball, this time with stainless steel cast nodes, connected by cut circular tubes as a basic system. The cost level was around 12 million D-Mark. He seemed still surprised and said that 2 big competitors were interested; each wanted to develop their own details. But in the mean time Gehry had told him to keep to his original design with the complicated finger-formed details.

ANALYSIS OF GEHRY'S DESIGN

The roof design encompassed a whale-like volume with a high and narrow end and a flat and low end on the other side, with a fluent triangulated volume in between. In fact there was a single layered space frame made of solid rectangular bars, connected by solid stainless steel nodes with 6 fingers, covered by triangular double glass panels of a special composition. The relative high slenderness of the structure gave rise to the danger of local buckling in the space frame shell under high local loadings, leading to progressive collapse and hence to possible collapse of the structure. For this reason all connections in tube ends and connectors were provided by double bolts so that the bending moments could be absorbed over all connectors.

For the purpose of stiffening the large shell surface three stabilisation trusses were designed, perpendicular under the shell surface, composed of tensile rods only, in the fashion of the stabilisers invented by the Russian structural engineer Schuchow and built in the GUM magazines in Moscow in early 1900.

It was clear that the geometry of the whale only knew mirror symmetry, so in fact all individual nodes, steel rods and triangular glass panels had to be engineered and produced as individual products. The entire job contained a number of more repetitive glass facades, roofs and floors. The design has been extensively documented in the 'Excursiegids Bout Berlin 2002' as an overprint of an article from Glaswelt, Juni 1999 [Ref. 02.02]. In this article a number of essential pictures have been repeated from the same source.

In the original design the nodes had the form of a hand with 6 fingers, cut from a flat plate of 40 mm thick stainless steel, after which all 6 fingers had to be pressed into the designed vertical direction, which was different for each finger. Some fingers even needed twisting. Each finger-formed node was different, no: unique. The precision of the ends of the bars with the double-lipped connections with two bolts was exactly calculated as the maximum by engineering bureau prof.dr. Jörgen Schlaich from Stuttgart. This implied that there was not any allowance for production or installation inaccuracies. This exact engineering, too exact engineering, astonished me, which I also put on the table in discussions with engineers of Schlaich's office. Their accuracy would imply immediately to the executing producer in case of overstressing. From that moment onwards I was not Schlaich's most favourite candidate for the job. The Dutch language has a special word for this: "instinker" or tricky challenge. Do your job exactly, but do not allow any inaccuracies from the makers. The expected problems were to be put entirely on the table of the producers. Not very social. After a few weeks of study and development it became more and more clear that I had to work out my own alternative, which was far easier to produce, had its own charm in design and would be much more economical in engineering and production.

LOGISTIC IMPLICATIONS OF AN EVENTUAL CONTRACT

A job of this complexity requires first of all an extremely skilled team of engineers, because all problems need to be solved in the engineering process. The project turnover was twice as big as the yearly turnover of Octatube, so dangerously big, even if executed in 2 subsequent years. Because in these two years the regular customers of Octatube also has to be serviced. We decided to found a semi-independent engineering department for this project. In this team Dingeman Korf with his experience independently running the construction of the glass facades of the Deutsche Bank/Guggenheim Museum at 'Unter den Linden' in Berlin would become the project leader. He would be assisted by two structural engineers, three 3-D draftsmen, an aeronautical engineer and a geodetic engineer. The aeronautical engineer was needed because of his experience with Catia, the computer software that Gehry's office used and in which the design was described. In the project specifications the Catia system was obligatory. It would take, for one workstation, $ 100,000. So, care had to be taken. These high costs were the reason that it was not popular in The Netherlands, apart from the pirate versions used by TU Delft aeronautical students, as the rumour went. It was said that the Catia system would contain 3D drawing modules, and compatible 3D statical analysis modules, so that complicated geometrical forms could be fully described in overall drawings, detail connections, structural analysis and shop drawings from one programming house. In fact one would need at least 3 or 4 stations simultaneously. We did not work out clearly how to buy one licensed package and have 3 or 4 engineers working on them simultaneously. But the main idea was to reserve a separate part of the office space for this project. This idea is still the same for a following large and complex project, not interfering with the daily Octatube business. In later projects, for example the town hall of Alphen aan den Rijn, and in the municipal Floriade pavilion in Hoofddorp it became apparent that each large or complicated project should have a senior 3D draftsman cum building technical designer in the lead of the project at Octatube's. The engineering of Blob buildings of Blob parts by a specialist producer takes place on the computers of his engineering department. The simultaneous co-operation on the 3D model in the same level by several engineers is not recommendable. There should be one main designer/3D computer model operator and the other engineers work on the 3D model in parts of a lower order, filling them in only later. The actual filling in of the main 3D framework will be done after checking and approval by the main designer himself only. This is all happening in front of the monitor, not on paper. A double check of all this work is hardly possible, as is the case in engineering of orthogonal buildings, which has the shape of 2D drawings. But the obligatory unique position of the main designer makes the project very vulnerable. Occasional illness of the main designer/engineer could lead in a catastrophe.

The architect of a Blob design has to work in much the same matter in relation to the co-engineering contractors. The architect builds, checks and certifies the 3-D model from a model of centre lines up to a fully materialised model, in progressive degree of minimal materials, material shapes in elements and components, connections between materials, elements and components towards the realistic sizes of all elements and components. He can dispose the 3-D model to the main engineer of only one engineering sub-contractor at the same time. This works similar to the 'slot'-times of aeroplanes. A pilot gets a slot time of half an hour or a quarter from the airport control tower in which he can start or land. When he does not use this he has to ask another slot time. The co-makers get their slot times from the co-ordinating architect in order to attach their pre-designed elements and components in the main 3D model of the architect. In the same time no one else is allowed access to the model. After installation of the co-maker the architect checks, and certifies the updated 3D-model and brings the model to the next co-maker, and so on.

Production would lead to a different type of approach in co-operation. Quite different from the engineering, which essentially has to be controlled from one hand and one place only, the production could happen in a lot of different places, depending of the specialism required for the different sub-productions. Compared to this the engineering of a Blob design is the core of the matter. Design is the cause of this troublesome route, but the engineering is the core of success. An architect who neglects the co-ordination in the engineering process, can hardly expect a perfect building according to the design in his mind. Actually it is my opinion that both the design process in his office as well as the engineering process with all the co-makers should be managed by the architect.

Smart structural engineers of the office of Jörgen Schlaich had prescribed in the specifications that the 'lucky' sub-contractor to whom the steel and glass work was contracted, also would be completely responsible for the statical analysis of the work. This engineering had to be redone by him. At the same time the Schlaich office would be discharged from its own responsibility towards the execution. This would lead to a contract where the sub-contractors would be handcuffed with laughing structural engineers on their back! I made my astonishment about this situation clear several times during the discussions and negotiations with the local representatives of the architect and the structural engineer, which they pretended not to understand. That is to say, it was understood very well, but was considered beside the issue. I made a correcting note in this respect in my final offer. This all happened in the time of tender engineering, before drafting the final offer and the tendering. One can imagine that the tendering parties of the architect and engineer were not very eager to enter into a contract with Octatube! Some time ago I heard from a source in Jerusalem where Gehry was preparing his last project (he claims), The Gehry was not very enthusiastic about the possible participation of Octatube in his Jerusalem project. In my opinion every professional in the building industry should be responsible for his own deeds. The architect has to fix the geometry of the building, the principle material choice and the form of the components from which his building is composed. The structural engineer should make the statical analysis of the building down to the behaviour of the different elements and components. If they take their rights but refrain from accepting their obligations and responsibilities, it does not seem correct to me. In the top of the pyramid of the project building 'team' rights (for profit and control) are accumulated, while the duties end up in the lowest layers of the pyramid (that is real execution and full responsibility for the final design and for realisation). I do not want to use the word 'outrageous', as these practices happen in The Netherlands more and more, and so Dutch parties doing business with my own company could make their conclusions of this statement of professor Eekhout. In my own office I have always taken full responsibility for design, engineering, production and realisation. But in those cases it was me who decided in co-operation with the architect the shape and details of the final design. The design has to be made by the designer, the structures will have to be designed by the structural engineer and the producing and building parties produce the designs fixed by architect and engineer only with their responsibility towards production and realisation. In case the sub-contractor / co-makes comes up with a design alternative of his own, based on his own experiences, that is more efficient that the original design, he has to show the structural consequences of this proposal and its compatibility. In such cases only the sub-contractor will join in into the game of the design. But certainly when the structural engineer wilfully positions the project details on the edge of the possible, showing off his eternal cleverness, while he deliberately neglects possible errors and usual and acceptable tolerances in production and realisation, and he disappears when complaints are made, then one could speak about an unbalanced development in the responsibilities in the building process. This top-down shifting of responsibilities and the bottom up concentration of control can only take place under the umbrella of ad-hoc building teams with a strong protectionist character from the client and a no-present participation from the constructing parties in the game. This can happen a few times, until after a number of failures and bankruptcies there are no constructing parties left who fancy these sorts of Free Form projects with the underlying responsibilities. Then it is published that the construction industry has not advanced that much or is incapable.

ALTERNATIVE DESIGN PROPOSAL BY OCTATUBE

As the complexity of the roof in the design of Gehry's was high, and certainly at the level of the overall geometry was not allowed to be changed, these was only one type of alternative in order to approach an understandable, producible and economical alternative with acceptable risks for the company. The biggest problem was not formed by the glass panels or the rectangular metal bars, although all bars were twisted which was not know by the engineers. The most complicated parts were the finger-formed knots with 6 fingers, each in a different direction vertically and horizontally, in order to follow the overall geometry. The root of the fingers in the hand would also give cause to a twist, a torsion. Without having too much critics on the structural design: frankly, I did not understand the logic. Most probably the architect only discovered in a late or too late stadium those twists in the nodal fingers and in the bars and did not want to spoil his reputation by changing the technical concept. For me there was only one clear alternative: spherical bodes and circular bars of the Tuball system which I invented back in 1984.

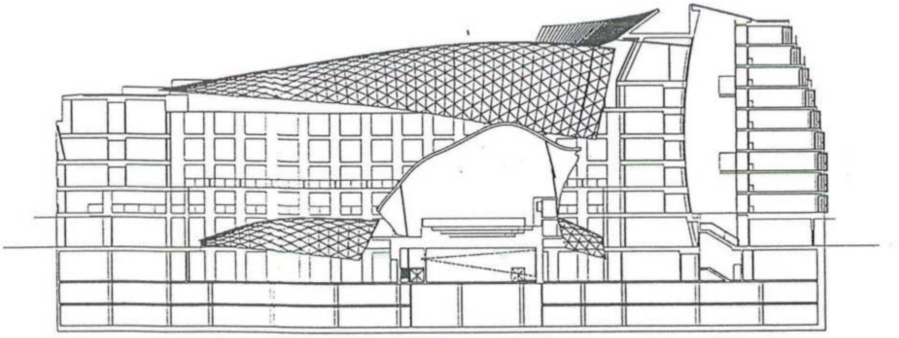


FIG. 21 Section of the DG Bank

From the many projects after that date I knew that all possible corners could be made by simply drilling cylindrical holes in the wall of the hollow spheres. Also for the glass support lines we had developed over the years a clear solution to clamp the glass panels. During the development of our prototype the German representative of the architect did not dare to go into confrontation with Gehry, so there the reference of the architect remained at the rectangular stainless steel bars and the twisted stainless steel nodes in hand-and-finger form. To illustrate our Octatube proposal based on the Tuball system: a number of illustrations are shown in figure 22 and 23.

THE TENDERING, THE NEGOTIATIONS AND THE CONTRACTING

The negotiations took place in Berlin. We were invited by a manager from Hines, a German building managing organisation. His goal was to close the contract for the lowest possible price, which he managed by playing competing parties off against each other. After the negotiations between the general contractors were over, Müller-Altvatter was the 'lucky' winner for a bid of 90 million D-Mark, while the first tendering prices were at 125 million D-Mark. I was told that the German frameless glazing company Seele had refrained from bidding, and that the competition was between Mero (space frames), Gartner (curtain walling) and Octatube (space structures and frameless glazing). During the negotiations it became clear that Gartner wanted to get the job at all costs. Gartner had always been the best and biggest curtain wall manufacturer in Western Europe, with a good name and many export projects. But many weeks were lost by negotiations, making proposals, preparing models, all while the completion date did not change. Three months later I thought the time ripe to organise a discussion with my biggest competitor from Germany, Mero of Würzburg, in order to come with a communal bid with each half of the engineering and half of the production, and hopefully half the profit. The price Mero calculated on the base of my alternative was 16 million D-Mark, the price of Octatube was 14 million. Together we put a bid of 15 million D-Mark for our alternative. Mero agreed this time: the original design was perfect but very complex and extremely more costly to engineer and to produce.

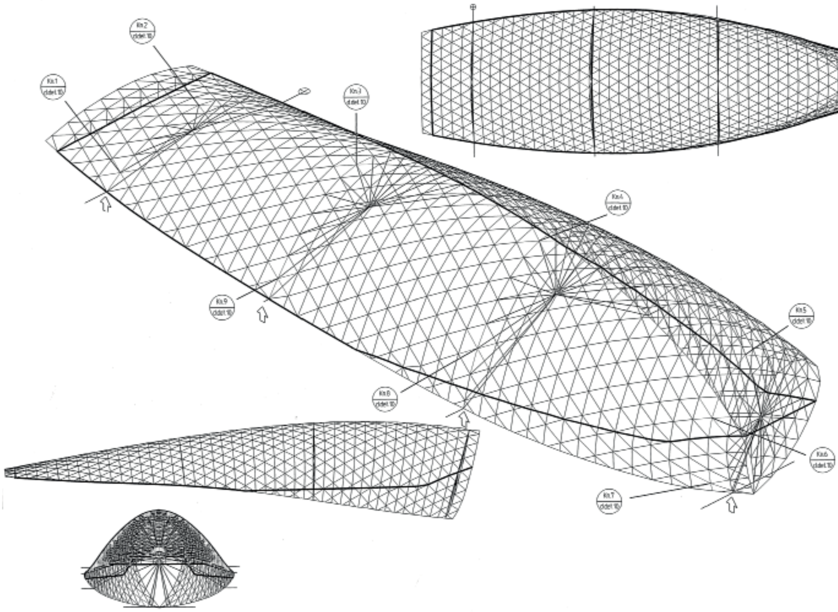


FIG. 22 Alternative geometry (Octatube) - isometric

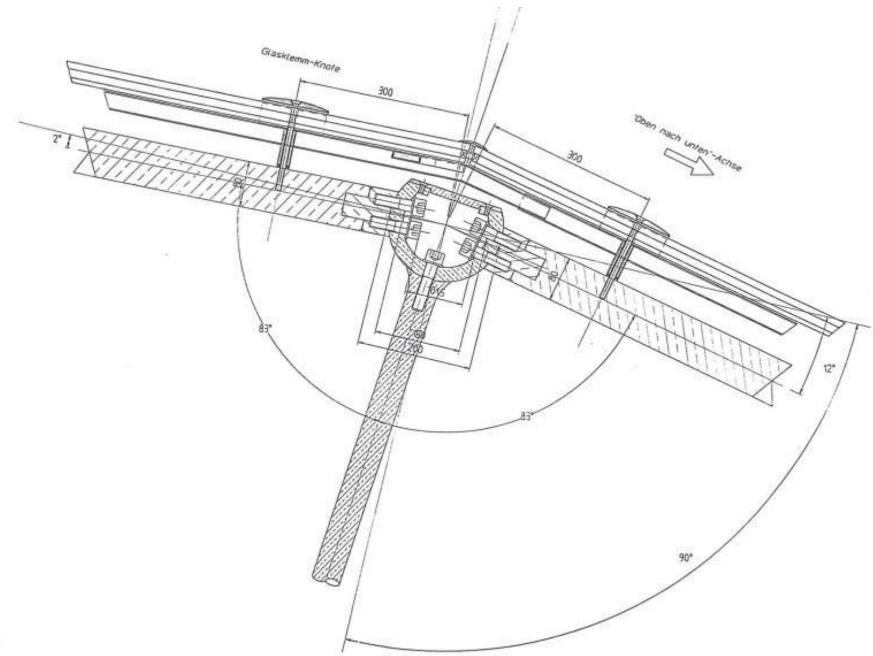


FIG. 23 Alternative detailing (Octatube)

Gehry's original design was put on the market for pricing via an experienced management cum financial costing bureau. Especially this management party was very successful in playing parties against each other. ASA bank, the DG Bank is an important customer in a low economy and hence parties would agree with a much lower price than usual. In order to keep the cash flow running, the personnel working until times would be improving. Selling under the market price happened a lot in Germany in those days and it has not changed much since then. The consequence of a bad economical situation since the 'tour de force' of the reunion of the two Germany's, the almighty position of the banks and the insurance companies were played out towards companies. Logical that the hunger for work made many companies buy projects literally far below their cost price. This harsh financial climate is not very attractive for German companies, let alone for smaller foreign companies. Slyness and mistrust dominate the games. And in my opinion, somebody is prepared to put a knife in your back. At the same time bankruptcies are regular happenings in the German building industry. No week without the bankruptcy of one of the German curtain wall builders. Until none are left. This project also added to this downward economical spiral. Read and shiver.

FIG. 24 Interior of the DG Bank

When writing this essay I presume that Hines played the game that they sort of leaked the quotation of Mero/Octatube of 15 million D-Mark as if it was a quotation on the original design. Gartner panicked, reduced the offer dramatically. The original price of Gartner was well above 20 million D-Mark, presumably even 25 million, went down to 18 million and with one last stroke was made a deal as 16 million D-Mark. The exact figures were never known to me, but my guesses have been deducted from the analysis my marketing manager in Germany, Rolf Evers, made. On the basis of this outcome the decision was easy for Gehry: 16 million for the original and 15 million D-Mark for an alternative unwanted by the architect and the structural engineer. Gartner received the order on the basis of the last negotiations, the price reductions. It was only later that Gartner heard that Octatube had always offered to the client on the basis of an alternative design and never quoted for the original. But at those times, it was too late for Gartner and it was too late for us, too, unfortunately. My impressions were endorsed when in October 2000 I visited Gartners exhibition stand at the Glastech Exhibition in Düsseldorf and gave a huge compliment to the original mock-up of the DG Bank on display. After I introduced myself to the staff, they exclaimed their despair.

After Gartner closed the deal we were in contact for a few months with their Gundelfingen office, trying to get a part of the job as a subcontractor of them. We had co-operated to the satisfaction of both of us in the double facades of the Guggenheim project in Berlin. But project leader mr. Merinda of Gartner judged this time that we were way too expensive. Maybe he was right. He decided to engineer and produce all elements and components himself. When I think of the financial results on this project, actually it is astonishing that he reacted like this. It must have been harsh for them, after they learned of Hines foul play, when I showed our alternative. Both Gartner and Octatube felt taken in.

IMPACT ON THE STATE OF THE ART

The DG Bank offers only limited occasions for visitors: only on Monday mornings, under a guide. During the 2002 Bout excursion this visit, around which the entire Bout travel programme was organised was refused at a very late date because of cleaning activities. It was not elegant at all. I never knew whether the name of the young organiser, my son Nils Eekhout, had something to do with it and other powers pulled the strings. But the photographs give a result that entirely matches with the original design of Gehry: super-ingenious watchmakers' work for the price of a bicycle maker.

Once bitten, twice shy is a common phrase. The reason that the original design of Gehry has been realised was not due to the intelligent design of Gehry, nor the almost too perfect engineering of Schlaich, blaming all possible problems up front to the 'lucky' contractor, but because of the cunning deeds of the project manipulator. I wonder whether Gartner would have made the same jump twice. Shortly after my visit to the Glastech Exhibition I learned that the famous Gartner company, the pride of Fritz Gartner for decades, had been sold to Permasteelisa of Italy, which also the manipulations of a German bank to make profit, ruining the national industrial pride in its wake. In a Detmold conference a former Gartner employee told the audience that the project cost was more than 8-9 million D-Mark.But the very completion of the original design of Gerhy for the DG Bank was an immense boost for complex spatial structures of steel and glass in building technology. The financial balance that was involved is not mentioned in the official publications. That is logical.

The technology attained is something Gartner can be really proud of. In line of the behaviour of architects it is likely that architects will copy Gehry's technical vocabulary, although his fishes and whales are clearly his own brand. Architects will copy Gehry. Rather, they will say: "we cite Gehry". The fear for the next step forward in the deep and whirling sea of the future building technology has disappeared. It is good to know that there always more economical alternatives can be developed producing the same effect in a more efficient way. But the realised transparent roof is an astonishing example of the art in engineering, art in the highest degree, for which the engineers of Gartner are highly praised.

When I travelled with my son Nils to Jeddah in spring 2002 we met an old friend of mine, Bodo Rasch in the aeroplane. I knew him from my working days in 1970 at Frei Otto's Institute for Lightweight Structures in Stuttgart. He had been designing and building big folding umbrellas and travelled to Saudi Arabia to sell the biggest he ever designed: over 100 x 100 m. He also told me that one of his companies, a ship hull building company in Malaysia went into liquidation as they had received a multimillion job for the horse's head in the DG Bank (below the glass roof) and could not finish it for this money. Actually it would have cost them triple the contract amount. This company was based on hand layup techniques of epoxy shells. It was another story of victims along the road of experimental architecture. Experimentation should go hand in hand both with courage and but even more, with prudence to last long.

02.04 REFERENCES

REF. 02.01 Mick Eekhout, 'Las Structuras Tubulares en la Arquitectura' (title of the Dutch version: Buisconstructies in de Architectuur' ISBN 90-75095-29-5

REF. 02.02 Gartner, 'Glas Architektur un Technik'', Glaswelt, June 1999, reprint in Bout Excursiegids page 202 to 218,June 2002 (hand out, 30 copies only).

03 MUNICIPAL FLORIADE PAVILION, HOOFDDORP

Mick Eekhout

After a limited design competition with four competitors, early 2001, the municipality of the Haarlemmermeer chose to realize the design of Asymptote Architects from New York (the architects Hani Rashid and Lise-Anne Couture): a pavilion for the Dutch Floriade 2002, to be opened on April 6*th* 2002. For six months, the building had to be the information pavilion of the municipality Haarlemmermeer and after that it had to be used as a café/restaurant in the park.

The competition design was located on the shore of the lake, but the realized building exists of an artificial peninsula in the Haarlemmermeer ('Haarlemmerlake') on which a building with two sloped roofs is situated. The big roof that covers the building volume harbours the entrance, exposition space and servicing spaces. The smaller roof is a freestanding canopy sideward to a dike. A continuous stream of water flows from the top of both sloped roofs, filling the glass pond and finally flows into two gutters on both sides of the entrance. The water streams visibly and tangibly, on the inner side of two glass walls, to the level of the lake. In several pavilions of the World Exhibit in Sevilla 1992, streaming water on facades was used as a climatic cooling system. But here it is only used as a symbol for the 'land of water'. Therefore the theme of the pavilion was something like 'Nederland Waterland' ('The Netherlands: Country of Water'). Not very surprising seen from the eyes of the Egyptian-American Rashid with his 'desert-background'. In the pavilion there are no references to the Floriade to be found, but the reference to the Dutch water landscape is excellent. For Asymptote this was the first building they ever realized in their 15-year-old careers as architects and a premiere in world architecture. The world-famous and many published 'Blob-designs' of Asymptote always remained platonic, up till then.
Up till January 8*th* 2004, the works of Asymptote Architects are exhibited at the NAi.

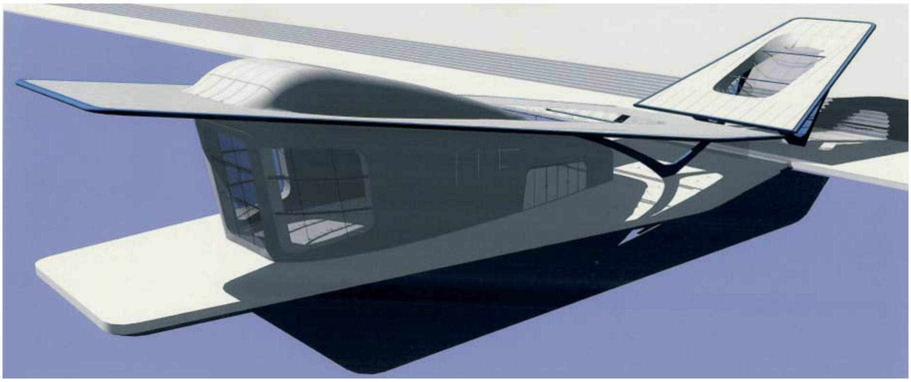


FIG. 25 Design by Asymptote

The architect's office of Anton Bronsvoort functioned as local materialising architect. The project management was, also on behalf of the client, in hands of Infocus Bouwmanagement. The main structural engineer Smit/Westerman and the main contractor was Nijhuis. Opposed to this usually traditional cooperative building team there were the co-makers who proved to be quite essential in this 'Blob' design: co-maker steel structure Smulders Duscon BV, co-maker ceiling and façade elements Van Dam (who unfortunately went bankrupt several weeks before completion) and co-maker frameless glazing and roof panels Octatube. Apart from the co-makers there were approximately 30 subcontractors, directly under the supervision of the main contractor.

03.01 DESIGN AND ENGINEERING

Initially there were high expectations of Asymptote's 'virtual office'. The idea consisted out of a central location on the Internet where participators in the project could acquire the most recent drawings of the architect with the help of an access code. On the faculty of Architecture we already tested the system three years ago in the 2nd year module 'Productie & Uitvoering' (Production and Realisation): and now it had already become reality! However, because of the lack of regular communication and the exchangeability of the computer drawings, due to the use of different software, the virtual office system did not work. The architect used Microstation/Bentley, the engineer X-Steel, Octatube and Van Dam worked with different versions of AutoCAD. During the process it became evident that there was no party in the design- and engineering process that checked, or was able to check the measurements of the drawings of different parties. All parties felt powerless, raised their hands to the sky and it simply overcame them. During the short period of an actual building project it became clear that there is no time to start up a general and good communication system between parties (to work with compatible computer programs) and at the same time to realize the actual shop drawings, engineering, productions and execution on the construction site. This 'firstborn' of realized Blob designs in the Netherlands showed the defects of the traditional infrastructure of preparation and execution of classical orthogonal designs. With the help of publications like these but also lectures conclusions can be drawn and strategies can be planned about managing the future design- and engineering process of Blob projects.

Asymptote drew with non-communicative software and had no possibility to transfer to AutoCAD, being the most popular software among co-makers and sub-contractors. The transfer between instruction (architect) and execution (co-maker) a lot of information was lost due to the necessity to export all files to DXF format. The accuracy of the computer drawings was lost and it was up to the co-makers to estimate the measurements of their assigned parts on the basis of those drawings. AutoCAD is purely software for drawing and is not suited for structural analysis. The steel structure companies in the Netherlands work with five different analysis and drawing software packages. In each of those packages it is possible to describe the geometry and the initial dimensions of the steel structures. This enables to analyse the influences of internal and external loads. These software packages are optimised for structural calculations and the production drawings for the resulting elements. Uniform engineering software is an absolute necessity to come to a feasible 'collaborative engineering'. In this case one could only speak about 'concurrent engineering' as it happened simultaneously. The difference is that in the first case there is cooperation, while in the other there only simultaneous labour. Collaboration in this project only took place by oral explanation and a fountain pen. But, being the 'firstborn Blob', the Floriade pavilion also had a guiding role. Despite the set boundaries of ICT, the partially very experimental High-Tech nature of the building and the often very traditional partners in the building team, due to an open collaboration under high pressure, this eventually resulted in a remarkable accomplishment.

As stated before, the design is composed out of two sloped roofs; one slicing the building volumes and the other containing a glass pond. Streaming water continuously covers both roofs. The design is the epitome of Blob design. The volumes of the building were not determined mathematically, but by geometry. Consequently the glass pond could not be described by means of regular mathematical equations. The co-makers (working parallel to each other and exchanging DXF drawings) tried to estimate the geometry of Asymptote's Microstation drawings as accurately as they could. Yet the glass panels of co-maker Octatube and the panels of co-maker Van Dam had a deficiency in positioning on site of over 125 mm! It would be highly recommendable to force the architect to draw in 3D AutoCAD/Inventor so all co-makers can work with the same 3D model and let the architect certify and safeguard it. Just like in the petrochemical industry, the idea is to have several co-makers take turns in filling in their part of the drawing on agreed slot-times (periods of time in which only one co-maker is working on the 3D model).

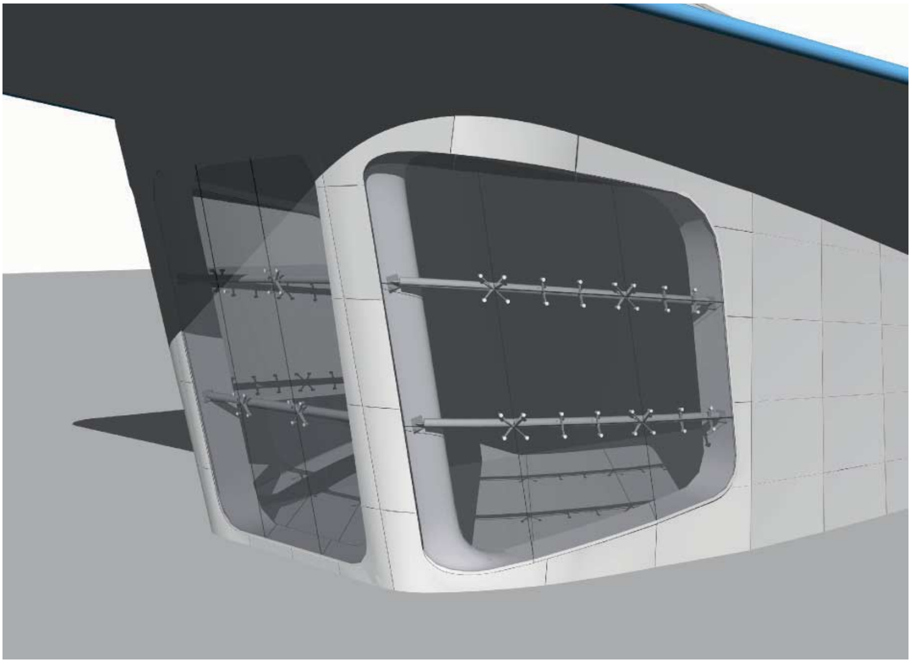


FIG. 26 Southern façade with bend glass

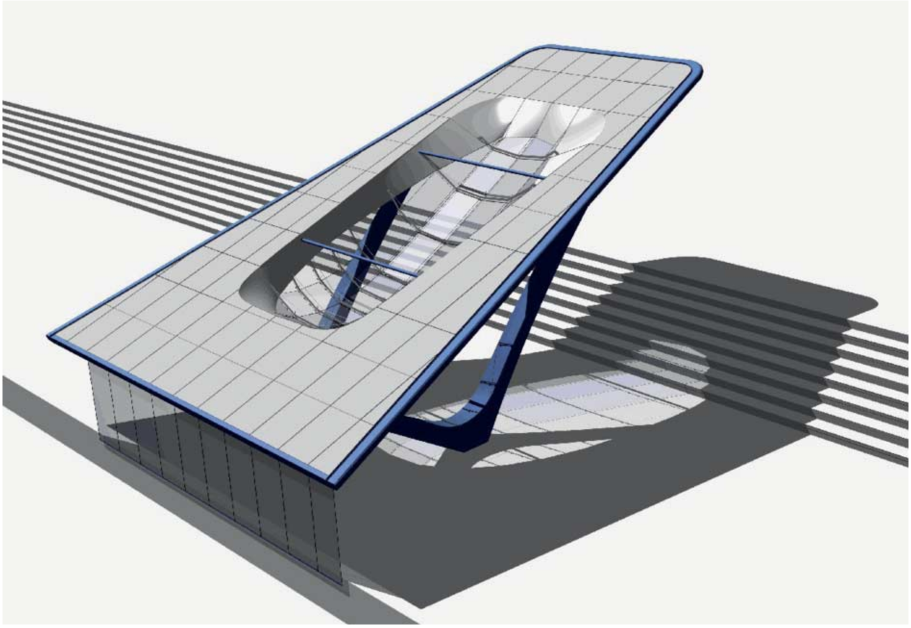


FIG. 27 Glass pond

The software package Catia (developed by French airplane manufacturer Dassualt) appears to be extremely more comprehensive, since several modules can both draw and analyse, but it is very expensive (USD 100,000 = for one workstation) and nobody in the Netherlands is willing to invest in this kind of software. Students of the faculty of Aerospace Engineering are probably working with pirated versions of this software. But the building industry is an easy-access-industry with a high level of competition, low volume and square meter prices. Consequently technology from the aerospace- or marine industry can be adopted, but they need to be adapted to cheap component prices for the building industry. A transition of technologies between different industries is obvious, the TU Delft with its open faculties offers a lot of good opportunities, which are gratefully used. The design and engineering process management for Blobs should be separately developed. Over 30% of the cost price is invested in design and engineering of all parties when it comes to Blobs. A good management of similar processes is absolutely necessary to accomplish efficiency in the process of preparation and realisation of Blob designs. Octatube manufactured and installed the aluminium roof, the glass pond and the glazing in the facades. Mick Eekhout, functioned as head designer in this component process and ensured that one of the three very experimental facets ended up at the Chair of Product Development as a research project (a third party funding) and was executed in its experimental status. The 3D exploded aluminium panels.

03.02 EXPLOSION PANELS

The 1st innovation are the 3D corners of the aluminium panel roof which were developed under supervision of dr. Karel Vollers (Chair of Product Development) as a third party funding. Vollers took his doctoral degree in 2001 with his dissertation on twisted facades: "Twist and Build" [ISBN 9064504105] and can be considered as a specialist in the field of twisted glazing and façade panels of buildings. He assembled a task force for the 3D panels with Dominique Timmerman of Octatube for the overall geometry, with Ernst Janssen Groesbeek of the Chair of Informatics for drawing the components, with Haiko Drachsta's computer controlled machined foam moulds, with Hugo Groenendijk's Exploform for the aluminium panels and for the assembly, fitting, sawing, welding, filling, spraying, installing and waterproofing with Octatube again. A goal-oriented team for a small (18 m^2) but experimental part of the building, which resulted in a renewal of production technology for buildings. The usual tension between time and finance on one hand opposed to experiments (trial and error) and not knowing whether you will attain your set goal was tangible in this project. But the task force stuck together and presented a technique never realized before in the building industry. Computer models had been made that subsequently were used to machine polystyrene foam blocks. The curved surfaces of those moulds were hardened with epoxy-resin glass. By pouring integral concrete (with short fibre reinforcement) an inverted mould was created. This mould was used as a sub mould for the explosion process. Hugo Groeneveld has a small company named Exploform that is located on the terrain of TNO Delft.

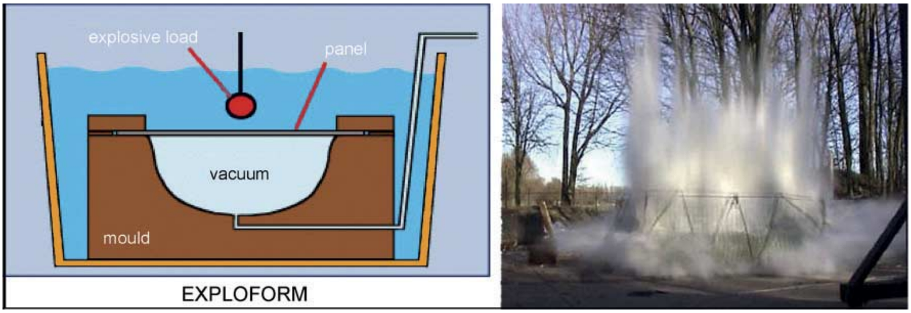


FIG. 28 Scheme of exploform process (courtesy: www.exploform.com)

He develops several production methods to transform metal panels in 3D. Initially we perceived the idea to place the positive moulds in water and freeze the water in order to use the ice to explode the panels on. Yet due to the high pressure the ice becomes water again and the mould is gone too soon. On top of that it would require a gigantic freezer. The idea was beautiful, but not feasible on the short term, since Explofrom is not able to manufacture a huge freezer for the occasion. Aluminium panels were placed on the mould, vacuum deflated and with the help of a water basin with a small TNT ring an explosion was generated that transformed the 5 mm thick aluminium plate with radial yet even liquid pressure in the shape of the concrete mould. The explosions caused the water and the plastic edges, also to be launched high up in the air. As a production method very experimental and far from industrial, but it proved that the desired accuracy could be attained. The panels had marks from the glass fibre on the epoxy skin of the negative moulds and had to be filled before they could be coated. In the factory of Octatube a wooden 1:1 mould was created in which all panels were fitted and equipped with aluminium edges, sawn, welded and grinded into complete panel component. Super inventor Haiko Dragsta recently developed a professional method to make cylindrical façade panels: With a CAD/CAM machine mould, as described earlier; aluminium panels are directly vacuum deflated and strengthened with a small foam layer and epoxy-resin so the shape does not pull anymore and can be regarded as stiff. This is the method he used to manufacture the corner pieces of the façade panels after the bankruptcy of Van Dam in the Floriade building.

FIG. 29 Mould for shaping the aluminium panels

FIG. 30 Completion of all bend panels for one side

FIG. 31 Opening for the bent panels

FIG. 32 Completion of the roof

03.03 GLASS WATER POND

The 2nd innovation in the Floriade pavilion is the hanging glass pond that is developed to take on the weight of 1,41 m water: 1,410 kg/m², which is 12 times as much as the average roof or wall load! As far as we know this has never been done before, not even in a James Bond movie. The original tender design indicated a water depth of 300 mm that gradually increased to 600 mm, 840 mm and finally in the definitive drawings, 1,410 mm. The weight load on the glass was reaching its definitive height. It was able to take the load; just a matter of analysis. Normal frameless glazing has a surface of 2 x 2 m, but in this case they were reduced to 1 x 1 m; resulting in a quarter of the bending moment. The heavy load caused the dot-shaped suspension (desire of the architect) to be transformed in a sort of dotted line support in a structural sense; a number of node-shaped suspensions with a distance of 300 cm next to each other in the width on the pond.

The shape of the pond was ideally designed by Octatube as a composition of fluent 3D shaped glass panels, 2 x 12 mm thick. The current state of affairs is so advanced (also because of the earlier described 3D aluminium panels) that it should be possible to machine foam blocks from CAD/CAM files and utilize epoxy and glass fibre mates to strengthen the surface and pour reinforced concrete over it in order to acquire a mould. When the mould has dried, it is covered with an isolating glass fibre blanket and you can gently lower glass panels in duo's of 2 x 12 mm at a temperature between 600°C and 700°C.

FIG. 33 Node-shaped suspensions

FIG. 34 Assembly of the dot-shaped suspensions

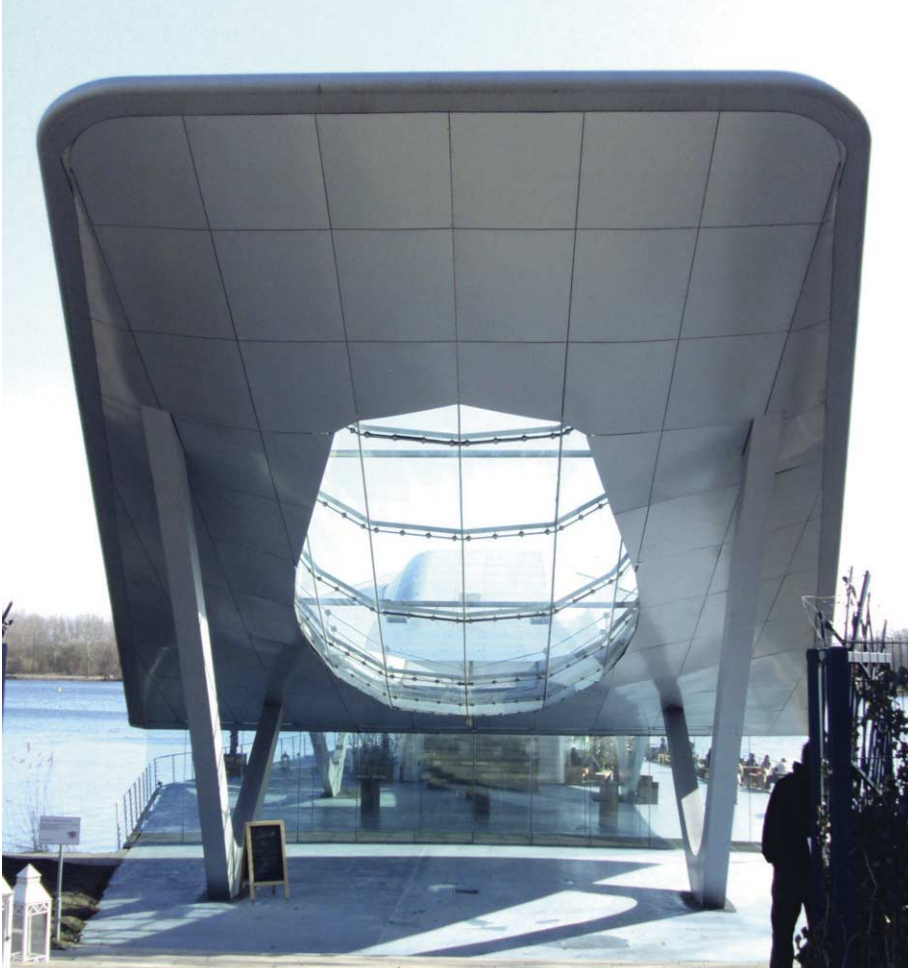


FIG. 35 Completed pond (without water)

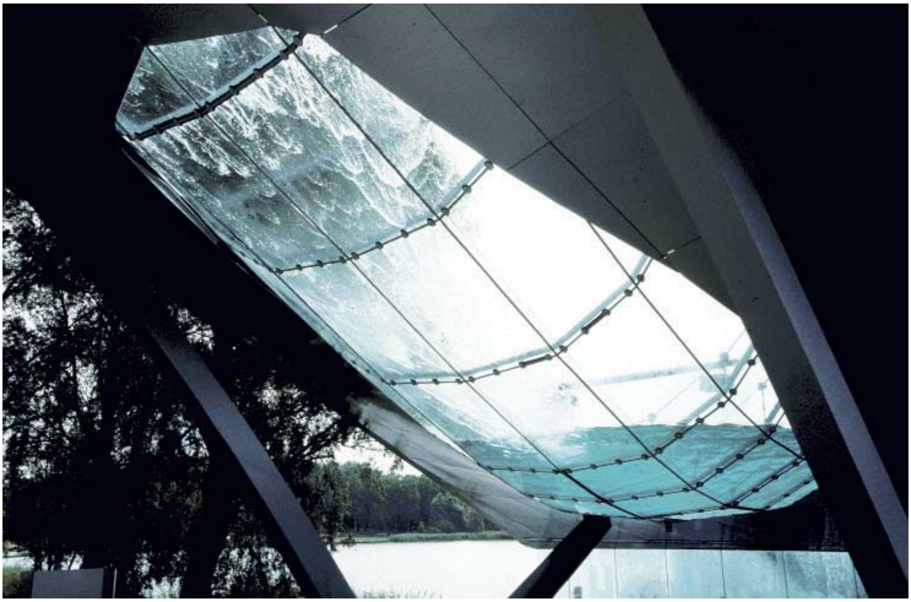


FIG. 36 Completed pond with water!

After cooling down, the 3D shaped panels with polished edges and which were cut in advance, were shipped in wooden crated to the factory were the chemical bath is. There are only two factories with this kind of chemical bath in Europe: one of them is Glaverbel in Switzerland. Chemical pre-tension: the sodium ions in the outer surface of the panels are replaced by potassium ions, which are bigger and subsequently cause a very thin pressure zone in the outer surface. This technology is highly developed for laboratory glass and produces guaranteed high tensions, usually twice as high in comparison to thermal pre-stressed glass. The chemical baths should be enlarged since chemical pre-stressed laboratory glass is usually much smaller. After the chemical pre-tensing, the nested panels are shipped back to the Netherlands were a transparent tape is applied in the spacing of 1 to 2 mm that can be filled with epoxy or acrylic resin in order to acquire a stiff lamination between the panels. Subsequently we have the problem of transportation to the construction site. This described production order is not used, since it is very expensive, labour intensive and transport intensive.

The danger of fractures is always present. In the case of the Municipal Floriade Pavilion, whereas a possible replacement could take up to several months, this would've been a disaster. Therefore a simpler solution, namely a polygonal variety, was chosen and realized. The fluent transformed and chemically pre-stressed laminated structural frameless glass was a bridge to far for client after all, but a persistent challenge for experimental product developers for next projects.

With the help of 2 x 12 mm completely pre-stressed glass, without holes, but kept frameless by elliptical dishes connected by seams; the first problem was the deflection under the continuous weight of the water. The second was the waterproofing of the pond and the third the corrosion of the water on the laminate in the glass panels in a moist environment. Eventually a liquid acid silicon from Tremco was used on the top to close off the upper laminates. For the bottom a grey prefab silicon profile was used (grey is the colour of all the other silicon on the construction site) and enables ventilation. Important in combination with the ventilation the laminate requires. If the laminate , under constant pressure of water and knowing the waterproofing of silicon, is under constant water pressure, the humidity could be sucked into the laminate due to capillarity and cause a white colouring of the laminate layer. The seams are kept wide since the glass opening on the top is 15 mm; the shape of the basin is round so the outer seams are much bigger.

03.04 COLD BENT FRAMELESS GLASS PANELS

The 3rd innovation is executed in the south façade. This façade exists out of three glass surfaces of approximately 6 x 6 m^2, each divided in 3 x 3 panels of maximally 2 x 2 m^2. The central glass surface is flat and exists of 9 flat panels of monolithic 12 mm completely pre-stressed glass. Both surfaces on the side are bent 2,5D. The original design consisted out of a conical and a cylindrical part. Making the conical mould was possible, but placed producing parties in Spain and England for big problems. That is why the architect was persuaded to alter the conical shape into a smaller cylindrical shape. The three stacked corner panels were manufactured as 12 mm thick monolithic thermal pre-stressed glass panels (pre-stressed by Interglass, GB). In addition 2 x 6 non-orthogonal panels, each 2 x 2 m^2 in laminated completely pre-stressed glass were cold bent on the construction site. From the beginning these glass surfaces were offered as polygonal.

The architect changed his mind, however, and desired bent glass. Thus an alternative in Plexiglas was calculated. Since the elasticity modulus of glass and acrylic differs by a factor of 30, the distance of the supports became 1 m instead of 2 m and the number of nodes became 4 times as frequent. In addition all the corners had to be bent and the thickness of the acrylic was increasing up to 20 mm: everything compared to the maximal wind load. Acrylic, suggested during a diner, proved to be no solution.

After that a distinction between the warm bent corner panels and the other cold bent panels. Cold bending of glass panels is highly exceptional or is always avoided. Cold bending took place at the construction site by pressing two points of the horizontal sides downwards with a camber of 80 mm over 2 m. The bending stress is calculated as maximally 50% of the total used stresses of 50 N/mm^2. The rest of the acceptable work tension (50%) is reserved for the wind load.

The laminated build up of these cold bent panels was chosen because of the danger of fracture during assembly. Cold bending naturally caused the phenomenon of too tall windows that only could be reduced to the right length by pre-tension (in horizontal direction). It also causes a deficiency in the vertical seams (which want to curl upwards) so a number of nodes on the vertical seams had to be applied. It must be possible to bend laminated completely pre-stressed panels weak and cold as cylindrical panels with a sufficiently low bending stress to take on wind loads. In this case a short span pays off to reduce wind moment and use several supports in order to make the glass thinner and easier to bend.

1 2 3

FIG. 37 Southern facade: curved glass panels

03.05 CONCLUSION

This prototype process showed that it is not easy to combine experimental and innovative production processes with the velocity and efficiency of a tuning building project, especially since H.M. the Queen performed the opening in 2002. The velocity of product development and project processing are completely different. Yet they entangle each other. As the experimentation is only concerning a smaller part of the project, its conditions are established by the tuning engineering of the project. On top of this, there is always the ghost of competition. Only when the total price is right, the orders are given. Pre-engineering is only done by the very experimental and smart architect offices. Thanks to much professional effort this time the building was completed just-in-time. But I will pass for such an experimental project with so much time pressure. With more time on our hands the technical results would have been far superior. The experiments in this project on laminated glass were awarded with a nomination for the DuPont-Benedictus Award of 2003.

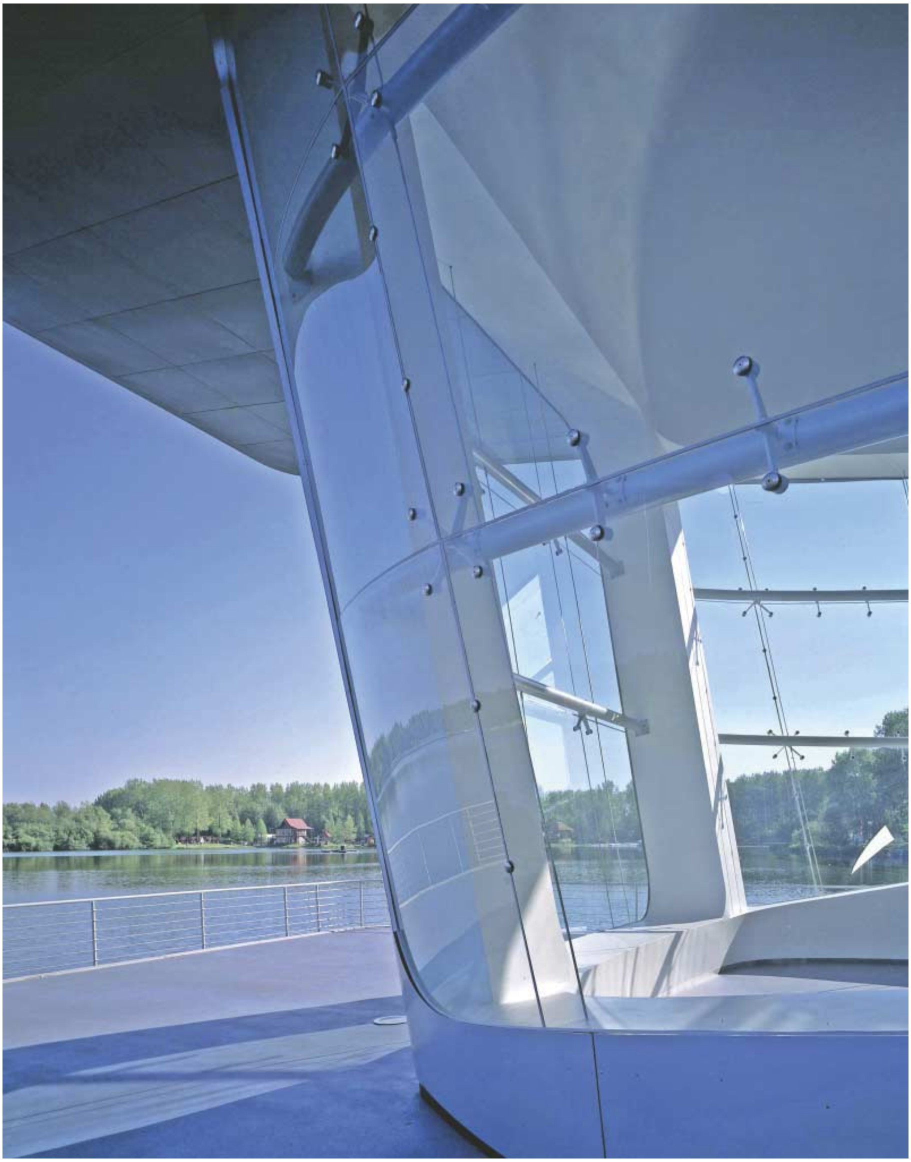


FIG. 38 Cold bent glass with fixing nodes.

FIG. 39 Glass pond

FIG. 40 Overview of the pavilion seen from the Haarlemmermeer

04 SPACE FRAME FOR PROVINCIAL PAVILION FLORIADE

Mick Eekhout

The architectural tendency towards Free Form Design produces a new type of buildings with a remarkable influence on thinking about spatial structures. An obstinate example of such a 'Free Form' or 'Blob' building was the design of Kas Oosterhuis, Rotterdam, of a pavilion for the province Noord-Holland, the Netherlands, meant for the Floriade, which was realized in April 2002. In the design stage, the architect Kas Oosterhuis and structural designer Mick Eekhout developed the structural design, up to a point where the architectural and structural ideas and finances showed unbridgeable differences. This contribution is mainly concerned with the various design considerations, which strongly steered the development process. After all, the most radical decisions are made in the earliest design phases. The significance of design decisions in the final phases of design and engineering has much less impact.

04.01 THE EARLY DESIGN STAGES

The preliminary drawing of the architect looked like a collapsed Gouda cheese: a round building with rounded sides and a somewhat dented roof. The estimated dimensions in the floor plan were approximately 24 metres, the height of the edge was 7,5 metres and the centre height 5,5 metres. Although this was an obstinate draft with regard to designing, it was still very much related to the long years experiences of building dome structures because of its rotational symmetry. The negative curving in the roof would be a reason for a double-layered realization, while the rest of the dome would basically be single-layered and three directional.

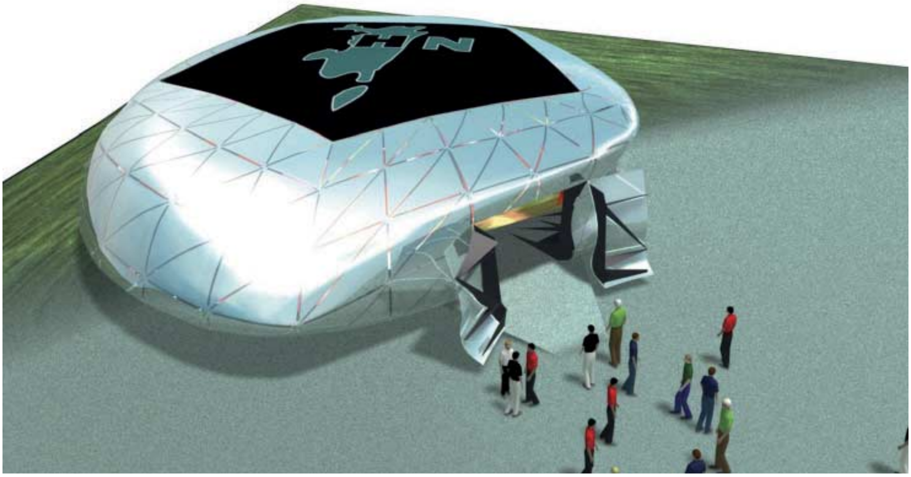


FIG. 41 Initial design of the pavilion (design: Oosterhuis.nl)

The second version of the design of the architect showed a rounded triangular shape, much like a Brie cheese wedge. Other shape associations use the terms 'cobble' or 'potato', or more respectfully, a spacecraft. The dimensions in the floor plan were 27 x 20 metres and 5,4 metres in structural height and 6,3 metres as the total height. From the dialogue between Oosterhuis and Eekhout arose a structural concept for a single-layered space frame with universal joints, connected to bars into three directions. This concept would be capable of handling the irregularity of the geometry, but was also based upon a record of accomplishment. The cladding and the space frame would be parallel. The second design did not have any rotational symmetry anymore. It was fully arbitrary in its shape and so showed suddenly a serial size for the production of one piece for all components. By that, the industrialization factor between the two described models seemed backdated two centuries.

04.02 SKELETON

The familiar dome models from the latest history of three-dimensional metal dome structures show the single-layered domes for smaller spans and double-layered domes for larger spans. Furthermore, the nineteenth century geometry is orthogonal, with radial ribs and horizontal rings, the type Schwedler. The twentieth century domes are all based upon various domes of Fuller are familiar: network models with horizontal rings and parallel lamella/delta girder models. The dome models that are composed of triangles, all have a similar material efficiency, which is much greater than that of the orthogonal models.

Usually, all these different dome models are half, or less, spherical, their height is less than half the diameter. Only rarely, domes are made ¾ spherical, i.e. radomes. In the eighties, Mick Eekhout did research into a 60 metres three-quarter sphere in Rotterdam. The structural analysis and the soldered (1: 100) model proved that the greatest forces would occur in the bottom bars of the dome. Three-quarter domes suffer from weak knees. This phenomenon would also clearly emerge in the Floriade design.

In the history of metal dome structures, the globular shape of the single-layered domes has always been fully synclastic. One of the few exceptions was the Multihalle of Frei Otto, Mannheim, Germany. There have been scientific analyses of the collapse of single-layered metal domes, where a small indentation in the synclastic surface, a local failure of bars and joints, had a catastrophic consequence for the stability of the entire dome and resulted in a total collapse. The Floriade design had a hollow, an indentation in the upper part of the design, to which the architect, from design considerations, was much attached. A solution to this intrinsic problem could be two-folded.

- The local extension of the single-layered system to a double-layered system;
- The removal of the indentation and make the entire surface synclastic again.

Overall, the above considerations illustrate that the architectural design was propelled by the possibilities of sculptural designing on the computer, as opposed to the acquired experiences and regularities of the design and building of domes in the last decades. Therefore, in the first discussions between the architect and the structural designer, these considerations came up extensively. For each experiment, the challenge to the designer is a motive of great importance. In this case, the challenge in structural sense was to make the improbable possible and feasible. Architect and structural designer soon agreed on the following basic principles:

- Consider the object as a shell;
- Make the shell rigid by the triangulation of bars and joints;
- Make the shell rigid for loads perpendicular to the surface;
- To introduce either moment rigid connections;
- Or to introduce shape rigid spatial angles at the connecting points.

The necessity of shell effects and triangulation was agreed upon in the first telephone conversation. On the one hand, the dimensions of the triangles depended on long bars, rough angles and greater shape rigidity and on the other hand on the limit of the covering 'Hylite' panels: a propylene core between two ultra thin layers of aluminium, totalling in 2 mm thickness. These panels for this project would be supplied free of charge by Corus, their main establishment being in IJmuiden, in the province Noord-Holland. The size of the trading plates was 3,0 x 1,5 m². The number of panels was limited. Each triangulation causes much waste (up to 50%), therefore, the engineering had to make optimal use of the material. The structural concern was: the rougher the connecting angles perpendicularly to the shell, the greater the external loads resistance. Small angles around the joints often cause failure. Therefore, a triangular coarse-mesh netting was preferred over a fine-mesh one. The architect had in mind to project the model of an icosahedrons on the envelope of the object, whereby the way of the subdivision of the primary axes of the icosahedrons (five meridians) was characteristic of the dimension of the triangulation. Because of this optimization, four triangulation alternatives occurred, namely from a 5-piece to an 8-piece. With regard to the shell rigidity (per moment or per share), it was decided to take the risk of applying a single-layered hinging space frame to these relatively small free spans, with maximal sized triangles. If the structural analysis would show that the shell would not be sufficiently rigid, possible additional actions would be taken, i.e. a moment rigid joint, instead of a ball hinge, or of internal cross bearers that were functionally useable in the floor plan to be tightened to, or five short frame rigidities, diagonally on the outer walls, or of bow strings reinforcements.

It was well-considered not to make a choice for the usual schedule of deep ribs perpendicular to the surface and in an orthogonal system, for reasons of the expected large consumption of material, the relatively banal simplicity of such a schedule and the fact that de development of an internally ribbed structure is quite a common thing in aircraft construction and the ship building industry. For a new way of designing in architecture, the structural designer desired to develop at least a new and unique way of a lightweight structure. The architect was interested in building the object, in whatever realization. The basic idea of the principal was to develop the design as 'economically feasible'. Of course, in this face the industrialization factor played a part too.

The first design of the Gouda cheese was rotational symmetric. However, the architect already had made an arrangement of the icosahedron, which had internally exploded against the envelope of the object and so, the repetition factor was reduced. The result of these considerations is the pentagonal roof of the object. The walking about visitors of the Floriade cannot really see the roof. It was designed as a five-fold icosahedron roof: the five constituent icosahedron triangles were all equal, so that they provided a small serial profit with the production of both the skeleton and the skin of the object. The structure of the object has lost somewhat in consequence, in a scientific manner of speaking, but has won economically.

04.03 CLADDING

A subsequent consideration was the cladding. This would be made from 1,5 mm thick panels. The initial considerations were:

- the triangulation in the shape of the panels;
- the cutting loss of the panels from rectangular trade plates;
- the individualization of the panels and the edges;
- the maximum size of the panels versus the thin material;
- the relatively non-rigidity or flexibility of the panels;
- the necessary water tightness for the entire skin of the object.

The major concern was how to make the skin of the dome panels watertight. This was expected to be difficult, due to the high degree of individualization. The main task would be to make an envelope of fitting panels. As a second task, a waterproof membrane of PVC coated polyester fabric, suspended from the panels, would realize the water sealing.

04.04 PERFECTION DURING EXPERIMENTATION

From that concept, the thoughts of the architect and the structural designer led into two different directions. The architect thought that, if there is a watertight suspended membrane, then the seams between the panels do not have to be waterproof, or accurately connected. Moreover, in the space between the aluminium panels and the watertight skin, artificial lighting can be applied, so that the object would be line-shaped illuminated. The architect thought in terms of the object as an extravagant building with fanciful possibilities. To the structural designer, the aim of the development of the panels was to make them fit as accurately as possible in the side connections, so that a sealed watertight could be applied. He considered the waterproof membrane as a second moisture barrier, not unusual for buildings. It should be possible to put the progressing insights into practice for further assignments. After all, Blob designs have a rising popularity and are worthy of a sound development to bridge the increasing gap between designing, engineering and production.Meanwhile, the architect went on with the detailed design of the object. He found that, due to the largely visual character of the panels, the skin design could be semi-independent of the skeleton design. In terms derived from the car industry: the architect proposed to run the body independent of the chassis at the rear. This considerably complicated the individualizing of the panels. Initially, the panels would be parallel to the space frame. Now, suddenly spheres and hollows occurred in the cross-sections of the panels over the space frame, as a result of sculptural interventions in the shape model in the computer of the architect. The image of the American cars from the Sixties came up. This new wish of the architect, which gradually became a demand, would eventually result in an unbridgeable difference in opinion between the architect and the structural designer.

04.05 COMPUTER AIDED ENGINEERING

The architect Kas Oosterhuis is famous for his digital designs. He has worked in this field for over ten years and did not only a number of designs built, but he also published several colourful books. In the year 2000, the Delft University of Technology appointed him part-time professor. Thanks to pioneers like himself, new Blob designs are published all over the world. In general, architects explore the bounds of possibilities by means of their CAD expertise and increasingly advanced computer programs in which 3D designs can be made. However, these programs are not yet compatible enough to the usual engineering programs. For an example, the number of bars, joints and panels had to be derived from a generation list. The drawings were not sufficient. The DXF file, which transferred the computer file that was certified by the architect for the use of co-designers, showed many shortcomings. Only after many weeks of work, the geometric data became clearly readable on the, for engineering common AutoCAD 2000/14, but only for the computer operator. By the time the geometric data could be read, the structural data were still not suitable for a cost accounting. Because of the experimental nature of the draft design and the insecurity with regard to feasibility, the structural designer started work based on a commission for co-designing and pre-engineering.

The gap between the accelerating architect whose greatest focus was the design on the one hand, and the carefully operating structural designer whose greatest focus was on feasibility, became even greater. This gap cannot be bridged, because the computer programs the architect uses are not compatible with those of engineers and producers. Therefore, a classic dilemma emerges: to act alone (keep everything in one hand, basically how Octatube started in 1983, or communicate in collaboration with appropriate means. Maybe, the architect could have generated the entire project by means of his own computer programs, so that the sum of the architectural design, the structural analysis and the component breakdown could have been developed by one hand, while the structural designer only gave advice and the producer made his cost account as accurate as possible.

In the course of the three months of cooperation (between the end of February 2002 and the end of May 2002), the choice for a parallel way of working was made: concurrent and sometimes collaborative. The architect worked out the design and tried his best at forming proposals for materializing. The structural designer and his engineers (Karel Vollers, Sieb Wiechers and Freek Bos) tried, already in an early stage, to get acquainted with the essence of the work, the rigidity of the structure, the composition of the elements and components and the full water tightening, parallel to the work of the architect. They reached different conclusions with regard to their possible future responsibility and liability for structure and water tightness than the architect. The result was a continuous dialogue and discussion.

The total budget of the project was of a very decisive influence. The first estimate of Octatube varied for two alternative realizations from € 430,000 to € 630,000. Only one month later, when the commission was handed out, the actually available budget for the engineering, production and assembly of the structure, cladding, membrane, floor and two doors emerged: € 240,000. Calculated on a skin surface of 600 m², this meant a price of € 400/m², including two complex doors. This square metre price was hardly a realistic budget for an experimental project. The commission for co-design and pre-engineering was estimated at approximately 5% of the realistic budget, but was only accepted as an obligation regarding the inverted energy, not the obligation regarding the result!

The estimates were established as the sum of assessed individualized element component costs and the way of realizing the components. The great difference between the first estimate and the available budget proved that it was necessary to be modest in the degree of experimenting. Indeed, there is nothing wrong with a low budget, just as long as it is realistic. Nevertheless, in the current case, the estimate could only be verified after three months of design development, structural engineering and the development of the skin. Only by the time the layout of the space frame was established and computer analysis showed that the structure was sufficiently strong, rigid and stabile, the cost accounting of the space frame provided insight. Unit prices and the number of elements and components established this. Basically, there was no discussion on the economy of the space frame (56% of the budget), but all the more on the economy of the cladding.

FIG. 42 Exterior of the pavilion

FIG. 43 Interior of the pavilion

04.06 STRUCTURAL ANALYSIS

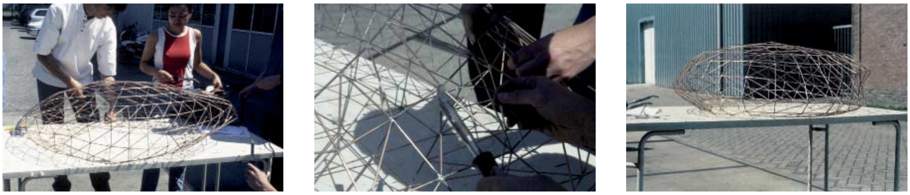
The second half of April was used to make the structural analysis. The Blob Graduation Building Technology student Freek Bos did this. Splines do not transfer correctly from Maya to AutoCAD. Therefore, much work was done by both parties to come to a proper computer communication. Via the pre-processing in FemGen, the structural analysis in DIANA and a post processing in FemView, insight was obtained in the behaviour of the frame shell. The indentation in the roof (with the possible local snap through as a result) was already removed in the network development. The introduced bars had the following diameters: 82,5 x 5,0 mm, 101,6 x 7,1 mm and 203,0 x 8,0 mm, the heavy bars on the five main axes, the meridians. Dead load, snow and wind loads were considered the main loads. As a result of the dead load and snow loads, the tail in the long diameter proved to flap up. Furthermore, the roof sagged by the deformation of the lower half of the bars: the knees. This was confirmed in the material model of the students. The remedies were:

- to enlarge the structural height of the shell in all cases with maximal 1000 mm from 5,4 to 6,4 metres;
- to make the bottom bars of the frame shell considerably heavier;
- to flange couple a number of bars on the five meridians, moment rigidly over the joints by means of welded flanges, by which tubular interconnected beams would occur with a diameter of 203,0 x 8,0 mm;
- to place five internal slender cross bearers on the meridians with a diameter of 101,6 x 7,1 mm, by which the entire shell would be parted into a flat roof and a round 'doughnut' wall;
- to introduce five internal meridional trusses to give the shell a great rigidity and which were acceptable to the architect;
- to introduce a number of shell rings to master the horizontal lateral thrusts, but through these, the two doors in the bottom edge would cut. This alternative was further neglected;
- to place five external outriggers at the sides of the meridians to strengthen the bottom sidewall. The architect did not appreciate this, though it strongly looked like the landing gear of a space vehicle.

The conclusion from this phase of the structural analysis was that, by rising from 5,4 to 6,4 metres and the internal strengthening by means of welded beams with a diameter of 203 mm on the meridians, a reasonably rigid frame structure was the result, with a maximum vertical replacement of 20 mm in the middle over the shortest span of 20 metres, which means a 1/1000 of the span. In other words, with still some approach cycles ahead, the frame shell would not cause unexpected and insolvable problems. The total of the estimated dead load of the frame shell with strengthening would amount to 600 m^2 over the skin surface, approximately 6,000kg. (10 kg/m^2).

04.07 CLADDING DEVELOPMENT

Problems seemed to concentrate at the side of the cladding. On the one hand, there was the strongly reduced budget of the client, and the architect who wanted a metal skin in its shape independent of the space frame on the other hand. Already from the first internal estimate, it could be concluded that there was too small a budget for an extended engineering of the skin, now that the skeleton was more or less roughly established. Though less desired by the architect, with the possibility of reaching a level of flat panels at the back of the mind, the quest for panels with a spatial curve began. After the architect had established the desired curves in the skin with regard to the centres of the joints and axes, by means of splines and nurb curves, it became clear that very complex 3D components had to be manufactured to fix the cladding to the required position in space, considering the space frame. Furthermore, a number of rather extreme cladding components had to be developed and manufactured. The required 3D nature of the cladding triangles was limited because the flat plates could only be folded or curved into one direction. Therefore, a triangle has a more or less flat centre and three points which can be curved upward or downward, independent of one another. The regularities of curving 2D panels into star-shaped 2,5D panels still have to be further exploited. Based upon these results, the definite offer was made with the bulged plating, a number of flat alternatives for panels and a stressed membrane as alternatives. Based on this outline of the costs, an agreement to go on could not be reached and the activities of Octatube ended there. Half a year later, the structural designer developed 3D aluminium panels and they were realized for the council pavilion in the Dutch Floriade. The costs for that project proved to be even higher than those estimated above.

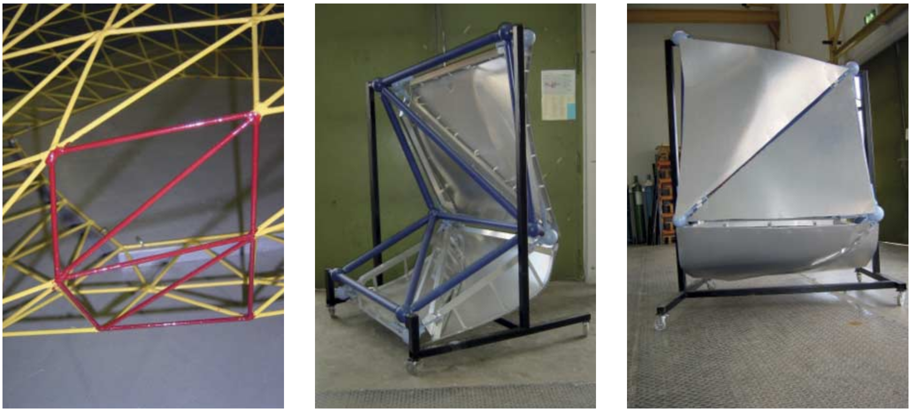


1 2 3

FIG. 44 Scale model made by students

04.08 PROTOTYPES

In May and June 2002, a group of ten third year Building Technology students has been occupied in the framework of an obligatory study part, named 'The Prototype', with two different parts. Half of the students had to develop a regular cladding component, as mentioned above, based upon a box-shaped component of which the body would run independently of the chassis. The other half was commissioned to design a workable door, fitting in the system, with a minimum width of 2,2 metres, opening turnable, swivelling, twistable or slewing. They derived their principles from the double hinging doors of civil airplanes. To obtain the necessary insight, a thread model was built first on a scale of 1:20, of 3 mm soldered coppered welding wire. After all the virtual models on the computer, at last a material model existed. The students learned much in these eight weeks, but the results of their work were not satisfactory. Their work confirmed the assumption that, within the given preconditions of the required design of the cladding, the necessary engineering and production efforts and the available budgets, no satisfying compromise was possible.



1 2 3

FIG. 45 Prototype of cladding, based on the tubular structure, made by students

04.09 FINAL REALIZATION

After the separation of the architect and the structural designer Eekhout/producer Octatube, the architect had to take another route. Oosterhuis never specifically asked for double twisted façade elements because he thought it didn't fit the budget. With the help of the consultancy D3BN, a load bearing structure was realized, based upon set steel strips of 20 to 30 mm thick and 100 to 400 mm high, in the familiar triangulated geometry. The strips functioned simultaneously as main support structure and as cladding fixation and were buckled to that purpose. The architect applied for a patent on this system. The cladding still had slightly bent flat panels 'Hylite' in a flat shape, fastened by means of steel braces to the steel strips, not being waterproof. The watertighting of the inner space came about by making the projection screen waterproof. By this, the project had indeed become a fancy and extravagant building. Yet, the building was realized. The dead load of the steel structure, manufactured and assembled on the building site by steel structure producer Henk Meijers, Serooskerke, the Netherlands, is 100 tons of steel. (The earlier space frame design was only 6 tons). The 'Hylite' skin weighs nearly nothing. The total costs for the construction and the 'Hylite' skin were € 250.000.

The intention after dismounting the pavilion when the Floriade exhibition has ended, is to build it up again with a new watertight skin as a 'Blob' laboratory at the Faculty of Architecture of the Delft University of Technology. The architect is developing a new watertight and insulating, fire- and burglar proof skin for this purpose.

04.10 CONCLUSIONS

- The lessons learned from the preliminary studies are fundamental and essential enough to put them before an international forum;
- The dramatic break in the development of systemized lightweight spatial structures, by geometrically unusual architectural 'Blob' structures;
- Blob structures bring along a loss of systemizing and repetition in the material load bearing structure;
- The high degree of individualization in engineering and manufacturing of the individual space frame components requires further research;
- The shift of critical attention from spatial structures to spatial cladding calls for design energy;
- Computer Aided Design enables to architects to make Blob designs. Computer Aided Engineering is vital for the establishment of the spatial complexity of the entire design and the individual establishment of the elements and components;
- In the near future, the digital bridge between Design and Engineering will determine a majority of the technical and financial feasibility of Blob designs.

05 TOWN HALL OF ALPHEN AAN DEN RIJN

05.01 CO-DESIGN PHASE

During the design phase, Octatube was invited to visit Erick van Egeraat Associates (EEA) several times, but Octatube was not under the impression that its advice was taken seriously. We discussed façade styles, distances and connections and the twisted section of the façade has been a topic during these talks in 1999. That part was the most attractive to Octatube because of its complexity and the experimental character. At that time, Mick Eekhout's Chair of Product Development at the University of Technology, Delft, did research into twisted facades, but this had not progressed sufficiently enough to be applied to this twisted façade regarding coated and screened double glazing. Dr. Karel Vollers was only to obtain his doctorate on this topic with the thesis Twist & Build [ISBN 090-6450-410-5] much later in February 2001. Because Octatube usually is extraordinarily interested in the challenges of complex structures, a commission with the theme of a twisted façade was awaited with great interest. In this phase, Octatube has supplied EEA with budget estimates on a regular basis, in the form of m^2 prices.

Because of the aloofness with which the orientation discussions were held and the fact that EEA clearly had other discussions with more parties at the same time, the responsibility of the façade design rested entirely with EEA. During the tendering, 'Spider' glass was prescribed, a product of the competitor St. Gobain. Furthermore, only a few companies, among which St. Gobain, could produce the glass width of 2,4 m. Particularly, the prescribing of a glass gauge that in Europe can only be produced by a few companies, sends the purchasing contractor into the direction of St. Gobain. However, the gauge of 8/6 mm with the given post distance of 2,4 m, as described in the tendering document, was as a combination in a class of its own. It is impossible to meet the Dutch or any EU criteria with the given column distance and glass gauges. Most probably, after the order, St. Gobain would have come up with an additional charge or change order request for the necessary 15/10 mm gauge glass at 2,4 m width, or would have decreased the glass width even yet. This ia a well known game. All this depending on the given designing responsibility of the executing parties, as described in the tendering plan. In any case, this topic had become an ever-present point of differences in interpretation.

With this, no earlier design suggestions of Octatube were recognizable or blameworthy to her. At times, it is an advantage when a producer has not yet been appointed at the tendering, since contractors will always look for an alternative, due to the habitual exercises in the Netherlands to economize after tendering. Tendering with more than one supplier usually causes a 'Wild West' situation of random scored prices, as compared to a procedure in which the parties of a building team spend their time together from the very beginning by means of subsequent estimates, all plausible and fitting into the budget. Apparently, the eventually offered price of St. Gobain was higher than Octatube's, because the quantity surveyor continued the definitive negotiations with Octatube.

In the spring of 2000, during the final tendering negotiations, there was a discussion with the architect on variants in the technical realizations and simultaneously with the quantity surveyor on prices and price reductions for variants. These tendering negotiations took place entirely based upon paper 2D drawings and a tendering document which was soon replaced by the written text in Octatube's quotation in which a few offer conditions were explicitly different from those laid down in the tendering document. Gradually, Octatube's suggestions, i.e. the ellipse-shaped façade columns and the smaller façade column distances, were adopted in the architect's drawings. Also the size of the glass panels, a different layout for the glass panels in the façade and the shape of the support structures in the frameless glass façade were accepted by the architect and worked into the drawings.

Initially, the façade was quoted in super neutral glass, after that in green-coated glass and then in clear glass with a decorative foil. The advantage of the foil was that, after a number of years and no doubt a change of fashion, this film could be removed. This would be convenient for a client who would have enough of the design, but the architect was adamantly against this proposal. From a technical point of view, a foil application would have a shorter life span than a screening in the same design. Eventually, by the end of 2000, the result would be realization with super neutral coated glass with an internal (in side 2) branded screening. The screening of glass or the application of foils was initially estimated as being a separate item, because of the unknown effects and the suspected gigantic negative consequences for production and logistics. The parties involved hoped that this cup would pass from them. It so happened that the architect's design provided for an utter individualizing of the screening that would result in the 835 panels to all be individually engineered and produced.

Five graphical designs were successively worked out by the architect's office: firstly a very wild design with trees which would need uncountable screening moulds, then a design with bamboo which already had some restrictions, after that a design with letters and numbers, a kind of graphic travertine design and eventually the final design of flower leaves and tree leaves. Octatube selected Lerobel, Hasselt, (Belgium) from the regular suppliers as the sub-contractor/co-producer of the glass panels, together with the company of IGP, Hoogstraten (Belgium) as the producer of the silver-coloured screening that would be branded into the glass. The definitive leaves design assumed a total of nine different parent moulds for the screening, upon which the layout of the various glass panels in changing positions and orientations could be established. IGP planned to realize this plan faultlessly, but, of course, errors lie in ambush everywhere with such logistics. In addition, such a task had not been realized before anywhere in the world, as far as we knew. If 'Murphy's Law' would apply to anything, it would be here. Lerobel would assemble double glass panels from the IGP exterior panels and the low-E soft-coated interior panels of Luxguard, Luxemburg. Due to the scattered component productions and assemblies, the internal transports and the individual designs of the different glass panels, it was assessed in an early stage already that subsequent delivery of omissions before completion would have quite a few time-consequences. But also, the breakdown of one single panel after regular production was expected to be a nightmare for logistics and costs. All this was reported to the client before the contract was entered into.

In the mean time, Octatube's prices were totalized, according to economy measures and all parties involved knew them. The façade structure was offered based on a centre-to-centre distance between the elliptic façade columns of 1,800 mm. When on the 3rd of March 2000, the quotation clearly fitted the required overall picture, Octatube moved on from quantity surveyor to the main contractor as the nominated façade subcontractor. The tendering of the façade was done separately, but simultaneously with that of the main tendering of the building. In consultation with the quantity surveyor of the project, Octatube came to a principle agreement, after which it was referred to the HBG being the main contractor. From the very start, the HBG regarded Octatube's work as a mandatory management supply, but within the building team, Octatube was positively considered as co-producer with the corresponding design & build responsibilities of the specialist.

FIG. 46 The front façade after completion

05.02 FROM PROVISIONAL TO DEFINITIVE DESIGN

From the start of the building team phase (April 2000), a considerable course of design development was necessary before there could be question of a well-organized engineering of all components of the building. This was caused by the geometric complexity of the building, the misinterpretation of principal details that all were drawn at right angles, while all intersections were proven to be oblique in different angles; the hesitation in providing the 3D data in a heart line model on CD-rom by the architect and the problems connected to the complexity of the geometrical measuring and controlling of the positions of components on site. Much time went by in the phase between tendering by the quantity surveyor, the transfer to HBG and the actual contract by HBG before Octatube considered the conditions on which all façade components of the particular building part 'glass façade' had to be engineered and produced clear and definitive. Actually, eight months passed between invitation to sign, before Octatube signed its contract. During that time, the building as a whole, as well as in her components, became increasingly complex. More and more incongruences were discovered and this caused more and more claims for supplement costs. Many discussions were held to get the interaction between the steel and concrete structure, as well as the façade structure clear and acceptable in terms of tolerances in the glass façade and deflections by distortions as caused by loadings on the main supporting structure, i.e. the 23 m long cantilever underneath the council chamber.

On the 30*th* of May 2000, main contractor HBG sent Octatube a principal order confirmation. The reasons for signing an altered contract text only eight months later were strategic considerations. Immediate signing of the contract could have meant that Octatube would possibly be liable to a contract that would be impossible to realize, with all its legal complications. Since Octatube is basically a technically driven company and not a financial/legal driven company and does not want to spend much energy on that particular aspect, we chose for this simple solution, much to the concern of the contractor. In the mean time, without a signed contract, Octatube actually worked on the design development at its own risk. The choice for working without a contract was made because in the period between Augustus and November 2000 ever increasing complications turned up from the engineering department, all of them having great financial consequences. All this while the client: Burgomaster and Aldermen of Alphen aan den Rijn had made it quite clear not to fancy the idea of extra costs. In a common tendering route, the occurring technical problems would have been covered by the clarity of the technical description that goes along with an entirely worked out tendering design and its subsequent price. The façade parts of the Town Hall project, however, one could claim, had been put to the market too soon, so that a definitive follow-up designing and engineering round was necessary, although the client did not recognize this as such. They had the idea to have tendered a completely designed and engineered building. Obviously, the client had the advantage of a set price for the current design, which is connected to early price making and therefore the convenience of oversight of the total price of the entire design. Actually, Octatube wittingly takes a design & build risk in many of its 'design & build' projects: a double risk, but usually Octatube is the most important player in the game. In the current case, the design phase was influenced considerably by EEA project architect ir. Ralph van Mameren who, as an independent player in the game, followed his own (EEA) route towards a stunning building with inspiring details and materialization. Octatube faced the risk of committing itself to take on an uncertain and increasingly complex engineering, for which the demand of individual screening of the glass panels could no longer be avoided. In this period-without-contract, Octatube took on the risk of carried out engineering (investment approximately Euro 50,000) versus the increasing complexity of the work in which nobody had sufficient insight, due to the fact that she anticipated possibly greater losses than invested in the engineering. In August 2000, it became clear that the fully loaded steel structure of the council chamber with regard to the tolerances of the frameless façade would bend to an unacceptable degree. Frameless glazing has a maximum deformation of 1 to 2 mm per sealant seam. ABT performed an extended re-calculation and re-dimensioning, with considerable consequences for the steel weight and the price of the steel structure. It also demanded an adjusted design of the details of the façade's joints in order to accommodate the required movability. In addition, the suspension of the façade posts from the roof, as initially agreed upon and permitted, proved to be not possible at all points, due to too low a rigidity of the roof structure. This period saw discussions on this topic in various design consultation meetings with the knives out!

05.03 FINAL PRICE-MAKING

After all technical problems were actually analyzed and solved, all complications for the engineering, production & realization were clear to the producer. One could say that between the time of the definitive offer/tendering (April 2000) and allotment/contract (November 2000), the technical design was made definite. On both sides, many sharp letters were sent with requests for information and recriminations of references to non-worked out aspects, which were of great influence on pricing and planning. Octatube did not accept the time consequences and penalty clause of the main contractor. In the mean time, Octatube's supplement costs were deemed correct and accepted by the HBG and by Burgomaster and Aldermen and amounted to approximately 25% of the initial offer. In total, HBG claimed supplements on several fronts which were agreed upon by the commissioner, up to approximately 20% above HBG's allotment sum. From that time onward, a period of relative calm began in which the definitive engineering was worked out, guided by frequent consultation between engineer coordinator Harry Pasterkamp (EEA), engineering leader Bob Kleuters (Octatube) and planning engineer Margriet Müskens (HBG). The resulting engineering effort, which amounts to an average of 18% with Octatube's projects, increased in this project up to 30% of the costs, for the major part blameworthy to the individualization of the steel and glass components. Over 5,000 drawings were made, next to hundreds of study files. For a comparison: the Eiffel Tower was built with 15,000 handmade drawings, but then it was as high as 300 m!

05.04 CO-ORDINATION AND INTEGRATION IN THE OVERALL DESIGN

The geometrical design of the Town Hall is characterized by a composition of geometrical systems, all of which lead to a higher level of complexity by their fragmentation.
The described geometry of the positions of the glass panels in the façade is no exception. It is a succession of circular systems with various radiuses, alternated with straight lines. The total description of the frameless façade can be subdivided in seven different geometrical zones. Zone 1, 2, 6 and 7 are cone-shaped, zone 3 and 5 are straight-lined in development and only zone 4 describes a twisted surface. With the exception of zone 4, the described geometry of the façade cannot actually be considered a real, so-called 'Blob'; the term 'Quasi-Blob' would be in order here.

INTERSECTIONS

The vertical sections over the façade know two different profiles in the geometrical sense. The one profile starts off at the west side and slightly leans forwards. This profile is buckled at the second floor level. The other profile starts off from the east side and slightly leans backwards. Both profiles develop from a horizontal point of view over the circular systems and at their meeting point, an intermediate zone occurs. This zone describes the twisted surface, which fluently connects both systems to one another. The whole of the frameless façade has a strong geometrical foundation. Only locally, they arbitrarily deviate, i.e. the torsion façade and the entrance area. The edge of the roof describes a very arbitrary contour, so that all vertical sections over the façade columns are eventually unique.

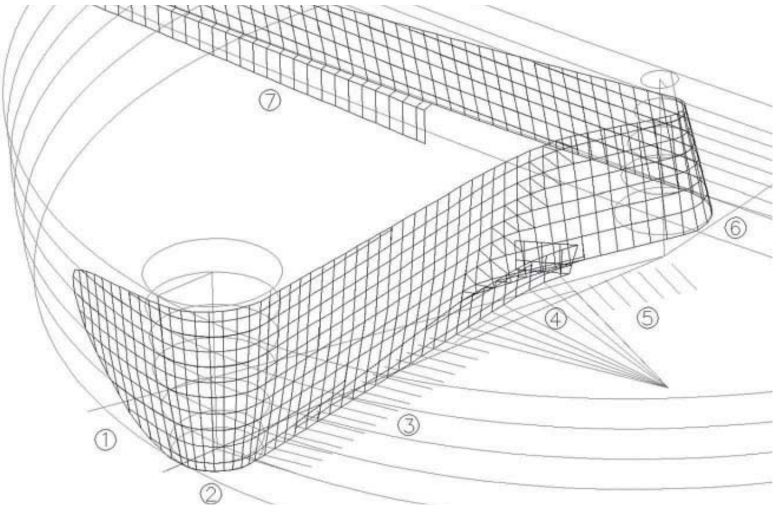


FIG. 47 Seven geometrical zones

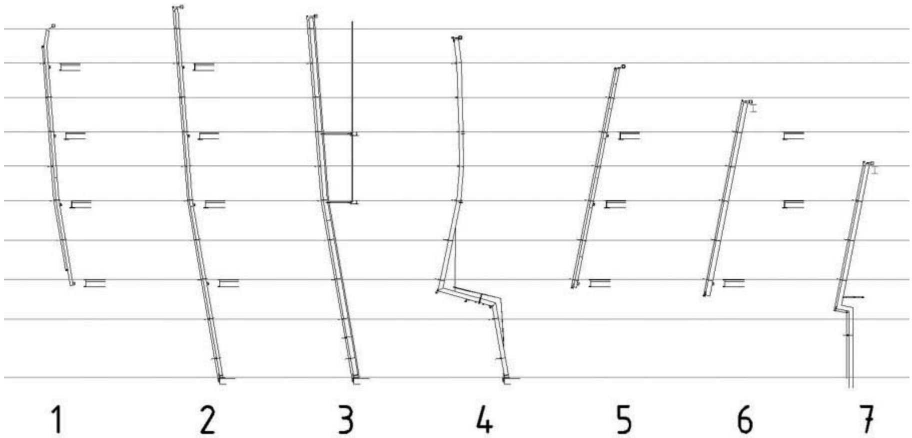


FIG. 48 Seven typical intersections

SEVEN TYPES OF ELLIPSE PROFILES ARE DISTINGUISHED	
Type 1	'standing' ellipse of the west façade, leaning on the steel structure at the rear
Type 2	'standing' ellipse located at the southwest façade, leaning on the concrete floor (zone 2)
Type 3	'standing' ellipse, located at the atrium in the straight south façade (zone 3)
Type 4	'standing' ellipse, located at the torsion south façade (zone 4)
Type 5	'suspending' ellipse, located at the southeast façade (zone 5,6)
Type 6	'suspending' ellipse, located at the east façade, internally made rigid because of the large free span (zone 7)
Type 7	'standing' ellipse, located at the east façade with the trimming framework girder (zone 7)

Table 1: Various ellipse profiles

The entire façade is built up from 109 elliptical façade columns, all individually different. To these, 650 glass nodes in 75 different models have been applied which tighten a total of 835 glass panels as filling-in components between the façade columns.

05.05 THE 3D-MODEL

The architect drafted a 3D model of heart lines and system lines described the architectonical design. The 3D-model was drawn in AutoCAD with the use of the mechanical engineering extension 'Mechanical Desktop' and it describes the principle coordinates of the building components, to be engineered and produced by the various (sub)contractors. Therefore, the 3d-model ranked at a very important place with the mutual coordination of the co-engineering subcontractors and the integration of the building design as the total composition of technical building parts.

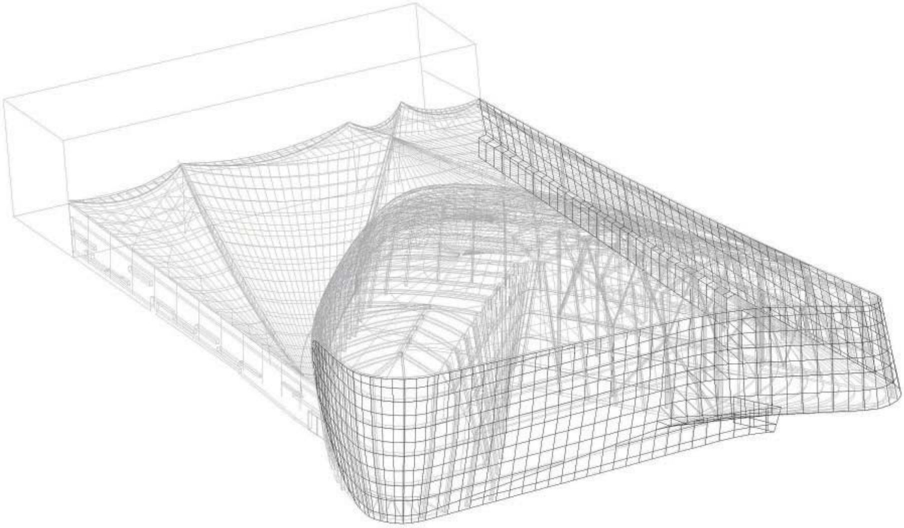


FIG. 49 The 3D-model of EEA with (in black) the frameless façade

To the positioning of the façade, the following data from the 3D-model were of special importance:

- position of the glass panels;
- position of the concrete floor at ground floor level;
- position of the concrete wall of the hind structure (east façade);
- position of the obliquely placed roof columns (east façade);
- position of the steel IPE façade column profiles (southwest and southeast façade);
- position of the steel roof edge profiles;
- position of the atrium bridges (south façade);
- position of the concrete stairway (south façade).

05.06 DETAIL ANALYSES

The central question of Octatube's engineers was: Where is the work of the third parties and how do we link up with them? Armed with the 3D-model based upon heart lines and the principal details of the architect, a large number of detail analyses was done. Furthermore, detail analysis were made of the supporting façade components (columns, framework girders and pended posts). All this in relation to the various possible production techniques that were halfway the by EEA required design and the functional structural characteristics.

The position of the framework located at the east façade was meticulously prepared in 3D. The available space between the obliquely placed columns of the main supporting structure and the ellipses of the glass façade could only be determined with the help of 3D computer models.

The roof edge detail was discussed extensively until it was developed to its final realization. The standing and suspending realization of this connection detail are visually hardly distinguishable. The standing version is equipped with a smooth stainless steel pen at the top side. The suspending version is equipped with a thread- end, completed with rings and nuts. They both form only one single point of coordination between the glass façade and the main supporting structure. This is convenient for the many different dihedral angles of the columns in the horizontal intersections. In addition, it was decided to connect the edge setting, which envelopes the glass panels at the column foot details and the roof edge details, to the ellipse columns by means of supporting strips or so-called 'little rulers'. By doing so, the façade, including all details after the placing and setting of the ellipses, could almost autonomously be completed. The alternative would have been to set the 'little rulers' at the rear structure, which would have been far more time-consuming. It would have caused the assembly process of the various contractors to become too much interdependent on each other.

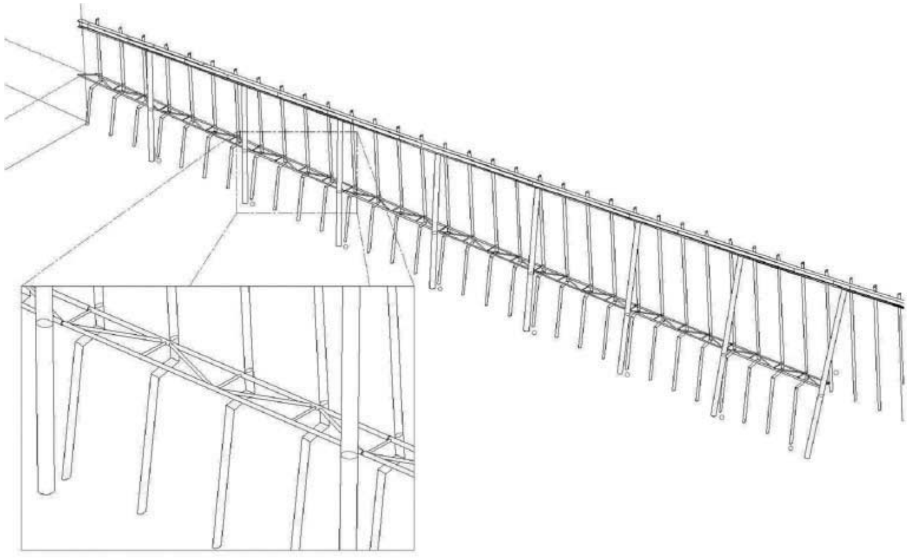


FIG. 50 The framework as located at the east façade

05.07 THE 3D WORK MODEL

Based on the tendering documents of the plan, i.e. drawings and specifications, a subcontractor usually develops his own working model. A work model for a building part with a simple geometry consists of a set of 2D drawings, together with accompanying comments. A limited number of ground plans, intersections and details describe all occurring details. Obviously, also 2D drawings were made of the glass façade. However, in this particular case making only 2D drawings proved to be not sufficient. Due to the complex geometry, the standard squared-angled representations of the various connections as they had been made, did not occur anywhere at all. These details had to be seen in 3D.

After a few weeks from the start of the definitive design phase (June 2000), the geometrical complexity made it necessary for the architect to pronounce himself in greater detail on the many connections.

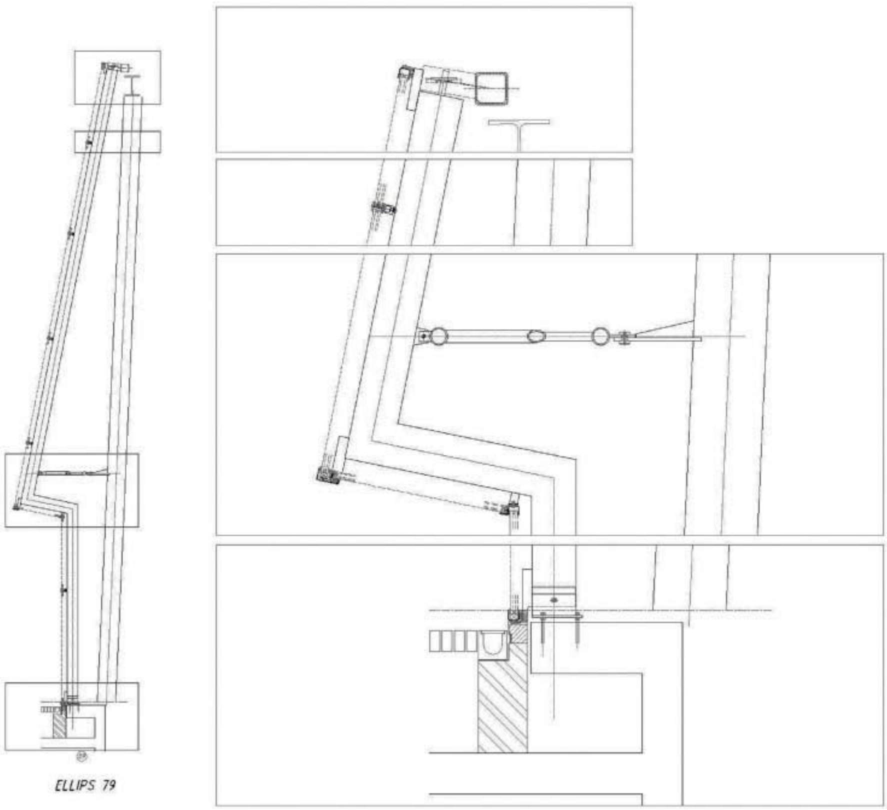


FIG. 51 Intersection ellipse 79 (east façade)

Based on the 3D model of the architect, Octatube set up its own special 3D work model. In this 3D work model, all engineering conclusions and actions were brought together. The 3D work model eventually contained a complete description of the building component 'façade' and provided a total insight in all interpretations Octatube had with regard to the ideas of the architect. Therefore, it had to be thoroughly studied. Approval of the 3D work model of Octatube meant no less than the clearance to make work drawings for production. Unfortunately, at the time of the testing rounds of the façade parts, a correct infrastructure for the exchange of such model was yet lacking. Therefore, the 3D work model of Octatube was assessed only in 2D and approved of by the client. For a following project it is an absolute must to have 3D work models of the various co-engineering producers checked, approved of and recorded (certified) by the architect. To this purpose, the models must be recorded in a compatible program.

Now, Engineering Office Van Veen, which was responsible for the engineering of the main supporting steel structure, had also developed a 3D work model. Van Veen's model was set up with the 3D steel package StruCAD. Via the generally known DXF-format, the 3D model could be imported into AutoCAD and subsequently compared to the assumptions of Octatube. By means of these unofficial checks, a finger could be kept on the pulse.

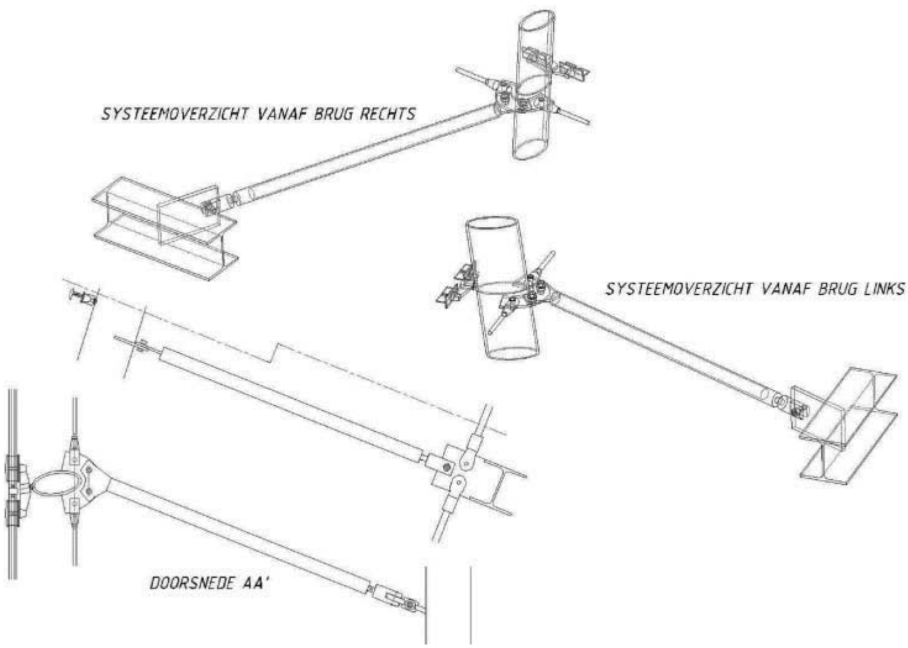


FIG. 52 Principle-building up of bridge connections, located at the atrium

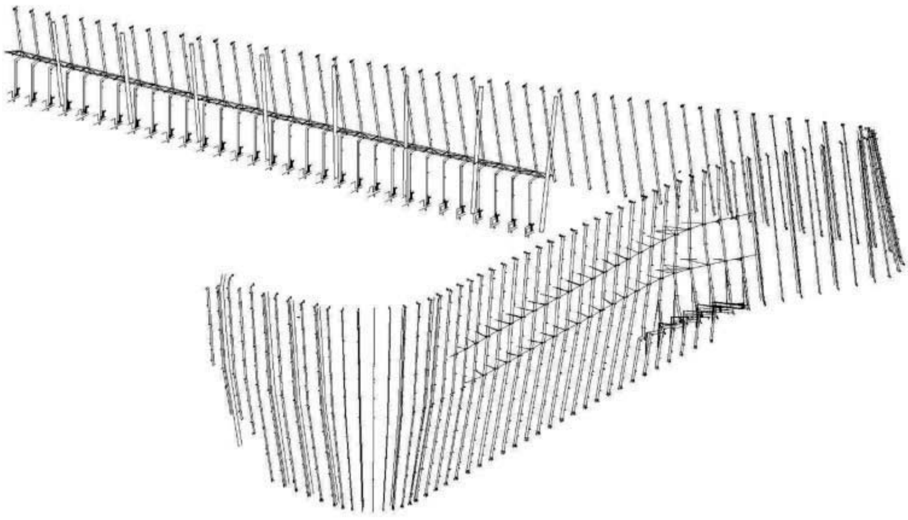


FIG. 53 The entire 3D work model of Octatube of all façade columns

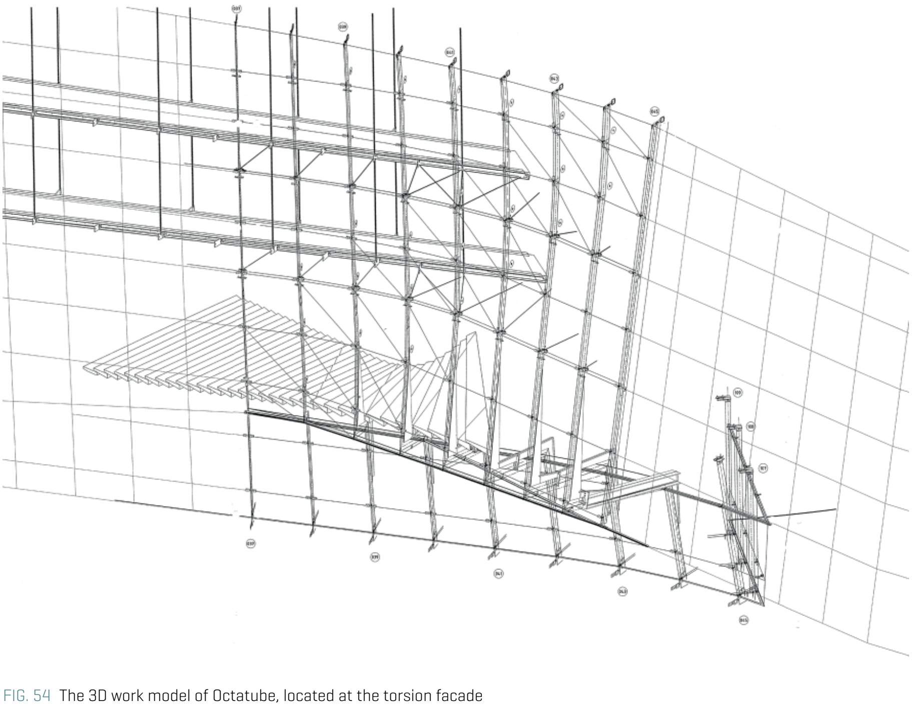


FIG. 54 The 3D work model of Octatube, located at the torsion facade

VALUE OF THE 3D MODEL WITH REGARD TO ASSEMBLY

The value of a very accurate 3D work model became particularly clear in the assembly phase. The geometry of the façade was set up by the contractor with the help of 'Total Station'. Through this system, the positions of small reflecting stickers can be accurately established. Such a measurement results in the x-, y- and z- coordinates of the measured point with regard to a point of reference that is determined in advance (0,0,0). Because this reference point was established at an early stage (already in the engineering phase), a correct coordinating of the work of all various parties was made possible.

WORK MODELS IN THE FUTURE

To the future, it should mean that all different work models of the various designing, engineering and producing parties (= companies) should form a perfect match. Due to the diversity of different development tools on the market, this is not currently feasible. Yet, it is important to take this direction actively and with expert knowledge develop all relevant aspects. The choice for the exchange format, the way of distribution and the way of assessment and control over the models are the central point. In the field of parametrical solid modelling, rapid developments occur and it is expected that within the near future this will lead to new useable uniform exchange formats for 3D solid modelling.

It is also recommended to determine the design and engineering management as early as in the planning phase, so that both the tendering and the organizing parties will know that their rights and obligations are recorded. The current planning only provides in obligations to (sub)contractors and hardly describes the responsibilities of the organizing parties. In this work as described, the waiting for each other made the progression of the engineering process very irregular.

05.08 SPAGHETTI GLASS STRIPS

In September 2001, HGB approached Octatube with an additional request, namely to think up an alternative for the elongated window frames (strips) of the rear side of the main building, the so-called 'spaghetti strip façade'. A producer of wooden window frames had engineered these façade strips for six months. These wooden frame strips formed for the largest part twisted glass ribbons between zinc strips of the coverings of roof and walls. The price for an alternative to the material wood (as prescribed by the architect) i.e. aluminium frames, was considerable, but because no decisions had been taken with regard to this building component in the same six months, the necessary time for preparation was no longer there. The main contractor called for Octatube's original thinking. Octatube's first concept was to make an identical structure as that of the skylights: double glazed glass panels, sealed to a structure of rectangular supporting steel sections. In the skylights, it is possible for these steel RHS to form a span up to 3 m. The initial idea was that the twisted frame strips could be made like this as well. However, when the wide variety in torsion of the individual panels as a new phenomenon became clear (for the most part 40 mm over a width of 900 mm), the idea of square tubes was immediately rejected, because the square planes would never perfectly connect to the twisted glass plates. The second idea, therefore, was to consider the frame material that caused the problem as being superfluous and only develop further on the basis of the strength and capacities of the glass. After a first analysis of how strong the glass was and a 'common sense' test of a cold twisted double glazed glass panel in the Octatube factory, the definitive proposal to have flat double glazed glass panels produced and cold twisted on site, could be developed. They would be force-rotated on top and bottom in a continuous U-profile with rubber fasteners and silicone sealant would glue this ensemble. It would become (as Eekhout reckoned) the world's very first cold twisted double glass façade.

The idea was to make a packet as flexible as possible of the thinnest and most flexible glass gauges and sealants in the rims. By means of a floating support with a circular disc fixed on a circular section, internal steel façade post centered in between the larger spans, (the maximum is 1,8 m) the required wind rigidity would be obtained. The bending tensions, brought along by the forced rotation of the panels, were only 7 to 10 N/mm^2, while the fully pre-stressed glass panel is proven to be capable of withstanding an approved total tension of 50 N/mm^2. There remained 40 to 43 N/mm^2 to take the tensions due to wind load. That was sufficient. On that basis, the quotation was made for double glazed glass panels 5/15/5 and for the oblique planes 5/15/4.4.2 (with respectively 4 mm laminated and 5 mm non-laminated pre-stressed glass with an air cavity of 15 mm). Although the risk was high, but the purchase costs surveyeable, the client could be offered a considerable reduction for the contract.A number of tests were immediately carried out in Octatube's laboratory, first for the engineers of Octatube, then for the supplying and also guaranteeing subcontractors of Octatube: Lerobel and Tremco as sealant suppliers and after that for the HBG and the client. Initially, the regular glass suppliers did not feel at all to guarantee according to the concept for Octatube. Tremco did it, but their guarantee does not go beyond the 'free of charge' re-supplying of sealant. (The same problem occurs when sealing double glass panels upon stainless steel disks in the regular Quattro glazing). Eventually, after a few discussions and the submission of the definitive calculations, glass supplier Lerobel put the required guarantee on paper, but with a few conditions by which Octatube remained the main risk taker.

The installation of the twisted panels was well feasible in practice, although honesty compels to admit that there was much more breakage while twisting on site than usual. The first façade in the world with cold twisted frameless glass panels of fully tempered double glass, was now an accomplished fact. For the rest, despite the warnings of the engineering parties, the design does not provide any possibility for upkeep of the façade strips or to clean them: there is no façade maintenance installation designed or realized and no service platforms has been designed, in spite of warnings in writing from the side of the producing parties. In the year after the completion of the spaghetti façade, TU Eindhoven student Dries Staaks developed a theory for cold twisting of glass panels at Octatube.

FIG. 55 Detail of the 'spaghetti' glass strips with cold twisted glass

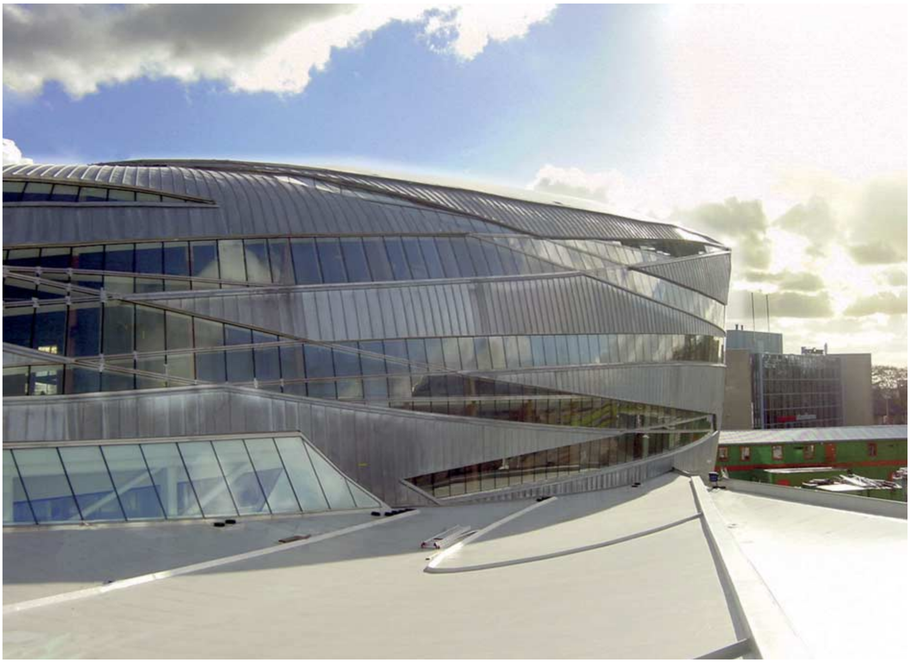


FIG. 56 Exterior view of the 'spaghetti' glass strips with cold twisted glass

06 GREENHOUSE, MALMÖ

Mick Eekhout

Not only the shape of the Green House in Malmö is special, the technical aspects of the project are also very interesting. The control of the complex geometry as well as the structural design were very carefully approached to ensure that both were up to the high standard a project like this was asking for. The goal set by landscape architect Monika Gora was to develop a structure with as much transparency as possible. She asked prof. Ian Liddell of Buro Happold of Bath (UK) to support her design in a structural scheme suited for tender. A major consideration was the realization of the glass house with flat glass quadrangular panels. This model was tendered for on the international market. Some Swedish companies as well as a Dutch company tendered.

FIG. 57 Model made by Monika Gora

At the start of the redesign phase after contracting Monika Gora provided a small physical surface model of the Green House and a 3D CAD drawing that the producer's engineers could work with. As the 3D drawing was not nearly accurate enough to develop a working basis for the further engineering process, a new computer model had to be developed. This was done using sophisticated design software (like Maya and Autodesk Mechanical Desktop). Rendered visualizations helped to finalize the shape.

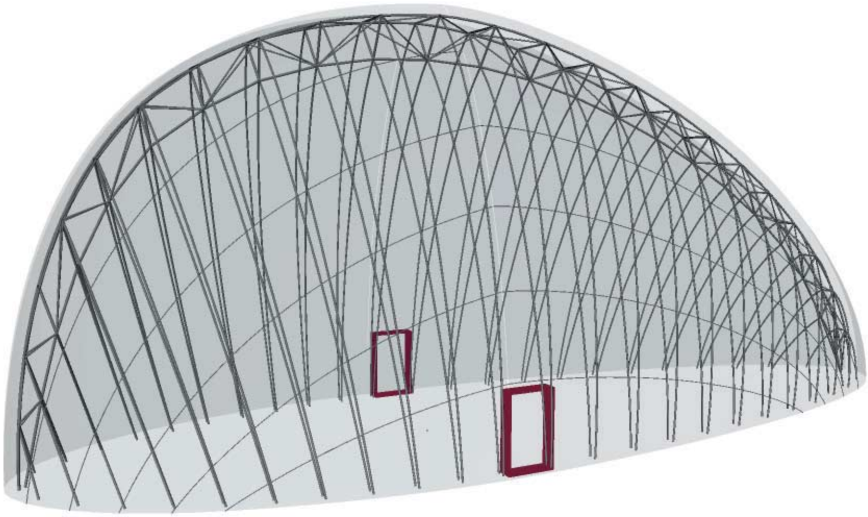


FIG. 58 The 3D model develeopd by Octatube, resulting pure application of flat glass panels

Early in the design process the decision was made to use only flat glass panels for the outside surface. Although the engineers had ample experience with twisted and bent glass panels the use of warm bent glass panels was ruled out, as the cost for cladding the complete building with free-formed panels would be astronomical. Cold twisted panels (panels pressed into shape on site) might have been an option but were also ruled out, as their twisted surface shape is difficult to control. Cold twisted panels normally form a hyper plane (known from tent constructions), which would contradict the chosen shape of the greenhouse completely. The challenge therefore was to develop a geometry for the glass panels that would follow the original shape as close as possible, while keeping all the glass panels flat.The challenge could have been solved easily if the surface would have been divided into triangles. This easy solution was abandoned, as triangles would mean much more glass divisions with extra silicone seams and glass nodes, which would lessen the aspired transparency of the surface. Instead a natural growth algorithm was used to develop a surface consisting of flat panels with four corners, starting at the highest point of the greenhouse and working onward and downward to both ends of the building. A couple of different divisions of the surface were worked out, adjusting the parameters for the generation of the 4 corner panels each time to arrive at a solution which had logical divisions and endings at all places. By using the natural growth algorithm it was made sure that all panels are perfectly flat, while every corner point of every panel still rests exactly on the originally chosen surface!

The glass panels are each made from two laminated, heat strengthened glass panes with each 8mm thickness. To get an as transparent façade as possible all glass panels were made from a special, extra white (low-iron) glass. Also the glass for the doors and the louver systems at the bottom are made from extra white glass. The glass material of these panels has a very low level of iron, reducing the normal, slight green tint of the glass to almost zero. A considerable glass thickness was necessary, as the site location of the greenhouse is exposed to high wind loadings, as it is situated directly on the shore of the Öresund between Sweden and Denmark.

FIG. 59 Overall view of the resulting glass house

As a principle glass node a special clamped connection in the seam between the glass panels was chosen. This connection consists of stainless steel plates, both inside and outside of the glass, with a plastic spacer in between. Four clamped glass nodes are fixed to one spider with four arms. Each of the spiders is laser cut from a steel plate and bent into the necessary shape. Due to the complex geometry of the surface none of the spiders is the same. A central bolt to the steel structure inside the greenhouse then fixes the spider. The clamped connection gives the possibility to use the glass surface to stiffen the whole structure, as each glass panel can transmit forces in its plane through the plastic spacer to its neighbour panel. This would have been impossible with a drilled connection due to the high stresses around the holes in the glass. The glass surface is therefore used as a continuous shell.

The structural design of tubular steel structure of the greenhouse started with the already developed divisions of the glass surface as a boundary condition. The structure had to follow the glass seams, as the spiders had to be fixed to it. Different possibilities were discussed:

- Delta trusses as columns,
- Delta trusses for the backbone,
- Plane trusses for the columns,
- Single layered space frame for the whole surface.

But in the end a very simple and clear structure of a double tubular spine and single tubes as legs was chosen. Along the ridge of the greenhouse (the backbone) a double beam made of CHS profiles ø168 mm was designed. As columns behind each glass seam CHS profiles ø159 are used. Overall this choice leads to a very clean appearance of the greenhouse, with a very high transparency of the façade. To minimize the steel structure, the glass surface is used as a shell to reduce overall deflections. The connections between the different steel parts are made by sleeve connections, to achieve a continuous appearance of the CHS profiles. All connections of the structure are designed to be moment bearing, to reduce the profile dimensions as much as possible. For production and assembly the highest accuracy had to be administered. Due to the choice to keep all parts as small as possible almost all adjustment space was left out. The glass panels were fitted into the glass nodes with a tolerance of ±1 mm. This tolerance between the glass and the plastic spacer of the glass nodes was then filled up by silicone strips, as otherwise the glass surface could not work as a shell and reduce deflections of the whole structure. The glass seams between the glass panels was made weatherproof by using structural silicon sealant. To make sure that all parts fitted together and all connection points for the spiders were fixed at the right place pointing into the right direction the whole steel structure was set up in Delft before being galvanized and coated. After all dimensions were checked, the parts were hot dip galvanized and then powder coated to achieve the best possible surface finish. Transport to Sweden and assembly on site went very smoothly in the late summer of 2005. Last finishing touches as well as the technical installations were done in the winter. The outside landscape gardening was finished in November, the inside in January 2006.

Realizing this greenhouse structure in Free Form design form has learned the engineers that the combined virtues of different structural schemes have to be employed; that insight in tubular structures has become ever so complicated. By combining the structural action of shells and space frames and even of structures with bent elements the resulting structures could be made. The engineering required a great many bent tubes pieces in very different bending radii. The accuracy of producing structures assembled from bent elements of different radius is well known. Appearing tolerances and neutralizing them in order to arrive at a structure with a high tolerance, dictated by the use of frameless glazing that cannot allow larger tolerances than 1 to 2 mm at very seam, requires a production and frequent 3D surveying during production and assembly stages. The result, however, shows a great optical logic.

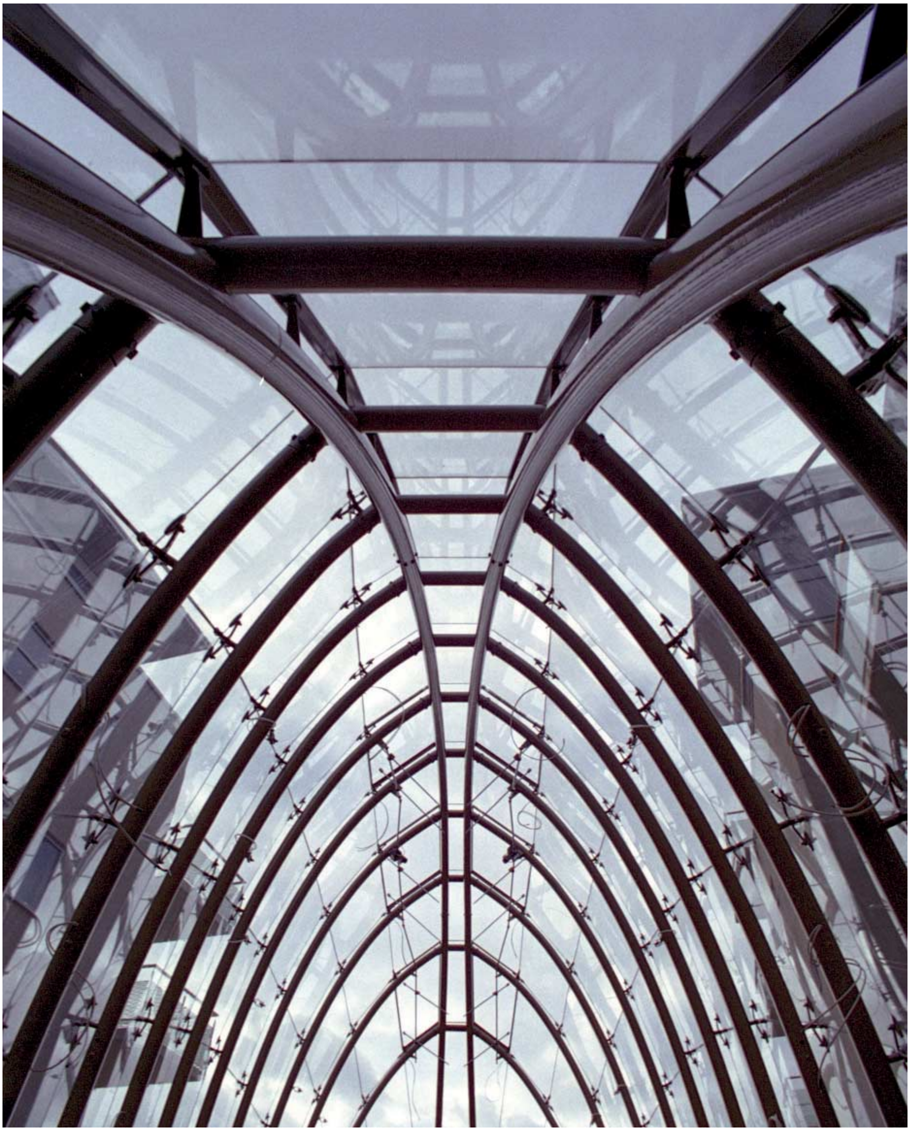


FIG. 60 Internal view of greenhouse with the facetted glass panels

07 COMPOSITE STRESSED SKIN ROOFS IN TEL AVIV

Mick Eekhout

07.01 INTRODUCTION

Technical design of roof and façade structures for architecture has accelerated in the last 3 decades from well-known traditional solutions into technically innovative solutions. After the development of stretched membrane structures in the 1970s, systemized metal space structures in the 1980s-, sophisticated tensegrity structures in the 1990s, glass envelope constructions and load bearing glass structures of the last decade it is now 'Liquid Design', 'Free Form' or 'Blob' architecture that caught the interest of young architects. The description of this type of architecture originates from a free form geometry, non describable with any regular mathematical formula. In a sense it is a direct consequence of technology driven interest of architects. Having learned the newest generations of 3D design and engineering computer programs, they are now capable to design (geometrically) complicated virtual 3D buildings that seem completely real on the screen without even being build. Yet the route to realisation is paved with numerous technical (and some social collaboration) experiments to produce the technical 3D components of these 'Blob' buildings. Often these components will be 3D-curved. Usually they are one-offs in their shape and non-repetitive. The extreme contradiction is the request for custom-made components versus the low budgets of the building industry on the one hand and researching and developing technological innovations in the speed of a real time building project process in order to acquire the new technology just-in-time on the other hand.

The aid of other design professions like aeronautics, ship design and industrial design is very inspiring and necessary in order to develop a new 'Blob' technology with the 3D forms, yet fitting within the modest average m^2 budgets of the building industry. Extension of the building industry's traditional integration is necessary in order to develop suitable CAD/CAE, CAM/CAB procedures and special production and surveying technologies. In this case producing one-off GRP stressed skin sandwich components made it possible to make larger spans for the roofs , though in an arbitrary form in order to become true 3D-roofs. Designing structural systems for use in architecture – including the necessary research & development, but always leading to actual realizations – is the core of the author's personal attitude towards designing. Many of the structural and constructional designs made as an architect, as a pioneer of space structures and as a structural designer, have followed an incremental approach of step-by-step with ever increasing know-how and elevated insight. This started for smaller projects in the Netherlands and led to applications of increasing scale both in the Netherlands and abroad. This approach is adapted to the (smaller) scale of projects in the building industry, their ever deviating character depending of the designing architects, their real time planning schedules and the desired degree of experimentation of the technical designer. The projects are performed as 'design and build' contracts in the Octatube company at Delft and sometimes in the architect's office.

The position as the professor of product development at the TU Delft and the range of collaborating faculties within the Delft University of Technology itself offer excellent opportunities for contemplation and sharpen the mind amidst of scientific design colleagues from different disciplines. This particular second congress of Delft Science in Design enables us to continue the debate on the merits of Scientific Design at TU Delft. To discuss the merits of design, development and research and to discuss the valorisation side of designing, developing and researching as the major activities of the TU Delft. Design is able to tunnel results of scientific research to society. The relationship between research and design are mutually indispensable. Some of the building systems, which were developed in the author's offices through time (see scientific site: www.mickeekhout.nl) have been boosted and accelerated by know-how from other professions, faculties and industries. Close traditional relationships are kept between architecture and (civil or) structural engineering.

FIG. 61 Architectural model of the Rabin Center, Tel Aviv (courtesy: Moshe Safdie & Associates)

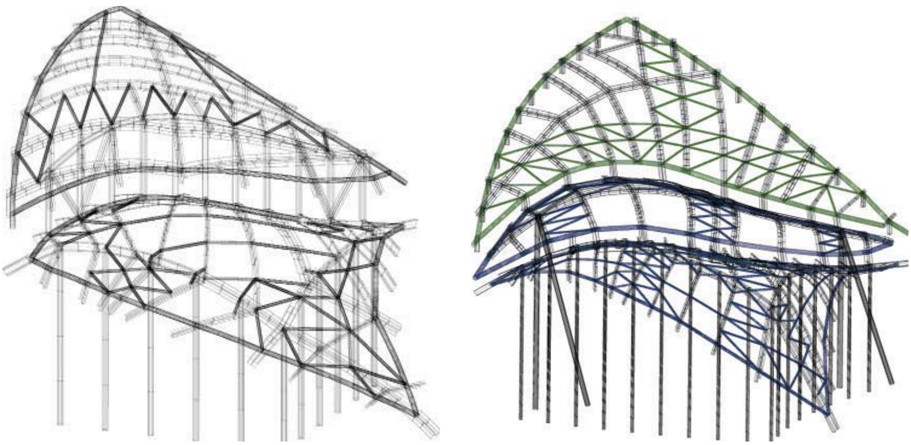
07.02 INVENTIONS, INNOVATIONS AND A COMPETITIVE MARKET

Amongst the ever-recurrent obstacles in component design and product development in architectural projects are the low thresholds in the building industry, the lack of interest in entrepreneurial experimentations and the overall tendency for copying the results of the experimentation of others, minimizing the experimental expenditure by the lazy policy of 'wait-and-see' or the 'me-too' effect. This is counter-positioned by the experimenting designer, dragging an office and a company behind him that follows his whims, willing and able to undertake all technical adventures in the process. This has been a life-long attitude.

After the initial product design and developments of a new generation of structures has resulted in successful applications, professional publications are written. After publication new clients become interested but the competition has been awakened, too this flow of happenings haunts every new invention. It was this framework that made the Europeans invent the protection system of patents in the 19th century. But with many different systems at hand and even more differentiated applications, patents do not shield inventive development work in architecture. The number of repetitions is low and the variety asked in different projects is high. The eternal fate of the architectural and structural designer is to look for new horizons: either new markets for existing products or new products for existing markets. Luckily a number of 'me-too' competitors for example in Israel made a mess of their copied systems, but alas these projects were lost in the tender stage any way. For the Hashalom (Peace) project in Tel Aviv the client regretted his decision to subcontract an Italian glass company for frameless glazing, changed his mind, withdrew the contract from that consortium and contracted the original designer company, who redesigned, engineered, produced and installed the project in a miraculously short time. Because the building calendar has its own speed. In the last years prices of frameless glazing systems are dropping due to competent and incompetent rivalry. Although experimentation with a large distance between production and building site adds to the possibility of a negative outcome, the composite wings of Tel Aviv are an example of a well-defined experimental component design & development for one specific project. After successful completion this could lead to an entirely world-novel technique of engineering and producing roofs for liquid design buildings. In its turn, this hopefully leads to the establishment of a new Dutch consortium of small and medium-sized enterprises (SME). It is further to be expected that after duplication, multiplication and systematization of the developed technology the laws of economics interfere and that the enterprising structural engineer has to develop ever new products and systems.

07.03 STAGE OF TENDER DOCUMENTS

In November 2002 the client "Friends of Yitzhak Rabin' issued tender drawings and specifications of a design by architect Moshe Safdie from Boston USA as a part of the Yitzhak Rabin Center in Tel Aviv. The design of the building was an elaboration and extension of a former auxiliary electricity plant near a university campus of Tel Aviv in order to become a memorial building for the late prime minister Yitzhak Rabin who was murdered in November 1995. He was seen as a peace maker and was rewarded the Nobel price for Peace in 1994. His activities led to the so-called 'Oslo peace talks'. The entire building was tendered out in different lots. This particular 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 Ayalon valley below. Both hall designs have remarkable and plastically designed roofs to resemble dove wings as a tribute to peace maker Rabin. Moshe Safdie is well known since he designed the dwelling complex 'Habitat' of Montreal as a part of the World Exhibition of 1967 when he was a 27 year old architect [Kohn, W. et al, 1996].



1 2

FIG. 62 Tender drawings made by ARUP. Left, 'The Library' and right, the Great Hall

This was the author's second collaboration with architect Moshe Safdie: the first one being the conical glass wedding hall of the Samson Centre in Jerusalem, overlooking the valley adjacent to the old city of Jeruzalem near the Jaffa Gate. Safdie is an almost prophetic designer who designs beautiful spaces with dramatic interiors. In the last decades he redesigned the Jewish quarter in Jeruzalem. The Samson glass dome, overlooking the ancient city with its golden colour 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 the alternative design proposals for the cone and with the realized technical accuracy. For the new project the complicated liquid design roofs of the Rabin

Center contained in the tender were analyzed by ARUP New York. They proposed a welded grid of steel beams in a rather arbitrary running of the open steel profiles with a layer of concrete on top. The specification left the roof cladding up to the contractors. On top of this the architect requested a seamless solution over the entire roof. Not a very appealing specification for a design & build company which had to transport all items over a distance of 5.000 km. 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 and the success would depend entirely on local labour and supervision, which a producer of industrial and prefabricated systems does not like. However, the client kept on reminding of the tender date and even postponed the tender.

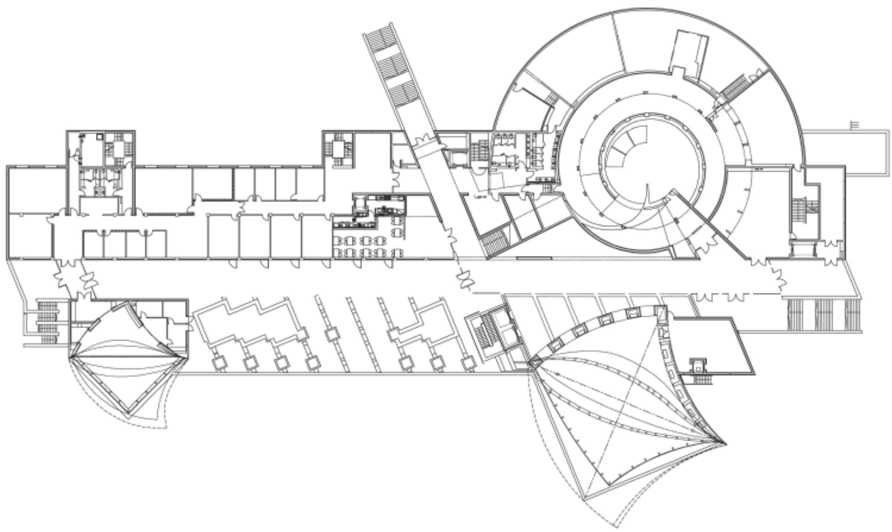


FIG. 63 Plan of the Rabin Center, Tel Aviv (courtesy: Moshe Safdie & Associates)

07.04 DEVELOPMENT OF CLADDING SYSTEMS THROUGH PROJECTS

When struggling with an alternative technical design for the new cladding of the Atomium of Brussels (dating from 1958), TU Delft's professors Adriaan Beukers and Michel van Tooren (Faculty of Aeronautical Engineering) stated in their inaugural speeches that "aeroplanes always leak and condensate" [Beukers, 2003; van Tooren, 2003]. This one sentence inspired the 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 x 8 spherical segments in the form of half an orange peel, size 14 m long, 8 m wide and 3 m curved. This resulted in a solution in which the total length of the seams was restricted to only 20% of the original joint length, which was 20.000 m'. Even a low leakage percentage of 1% would result in 100m' of leaking upper seams. In the developed proposal the joints were detailed much like 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. A patent was applied for. So in this case, an unexpected impulse from aeronautics helped to develop a new concept. Alas the politics around the tender were quite non-transparent and the contract for execution was awarded to a Belgian party. The design proposal keeps its value, however and is published here for its inspiration, returning to the alma mater of the original inspiration.

One year before the tender date 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. One of the three experiments in that project were 3D-aluminum panels of 5mm thickness which were deformed through explosion on negative concrete moulds (based on machined positive polystyrene moulds). This production process originally seems to have been used in Russian submarines in the 1960s. The paths of technology transfer are sometimes strange. This process took place at the premises of the Exploform company in Delft. This complete production procedure from engineering drawings, via Styrofoam negative moulds and reinforced concrete moulds, the explosion process, 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. It was the first time in the world that 3D aluminium panels for architecture were produced along these complicated paths. Although the cladding was successfully realized in this Floriade project, the m² price of the 3D panels was too high for a next project in the building industry (which in the Netherlands was also at the edge of recession at that time).

A cheaper system had to be developed for the next project. Haiko Dragstra, a very inventive mechanical/electrical engineer co-operated in this project from his company Complot, Delft 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. So these panels were half aluminium, half composite sandwiches.

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 did not like the idea of mixing different materials, according to the contractor. It was this line of thinking that brought the development further. Haiko 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 was subdivided in blocks and glued with the machined blocks of foam. Subsequently structural layers of glass-fibre reinforced polyester were applied to each side. These experiences came on the table when brainstorming on the new principles for the 3D wings of Tel Aviv.

FIG. 64 Close-up of the Atomium, Brussels

FIG. 65 Schematic drawing of the proposed division: 2 x 8 spherical segments in GRP

FIG. 66 First prototype with a stressed membrane.

FIG. 67 Third prototype to be locally produced.

FIG. 68 Fourth prototype, a prefab sandwich construction.

07.05 GIANT STRESSED SKIN SANDWICH CONSTRUCTIONS

So in a few brainstorms between designers and co-makers of different background , collaborating in a tender consortium, this was the basic idea: make the roofs as giant surfboards of foam with stressed GRP skins on both sides. The size of the roofs, subdivided into 5 different roof wings was maximum 30 m x 20 m. The company Polyproducts of Werkendam and her engineering office was invited to join the tender team of Octatube, as well as Haiko Dragstra. In a month time three successive brainstorms 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 the 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 curved CHS (circular tubes) with cladding variations in different foam layers, levelling and top layers was feasible from existing data and a little imagination. The cladding proposed for the original tender design was derived from the mega-sandwich idea, but now in a thinner scale version of 50 to 80 mm sandwich thickness, as it only needed to span the space between the steel structure elements (max. 3 m).

The budget calculations came out on a level of 2,5 million Euro for the original design with a thin 80 mm thick GRP sandwich cladding instead of concrete. The alternative design with the full load bearing stressed skin sandwich would add up to more than 4 million Euro, 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 injection methods. It was argued in the final brainstorm that the maximum extra costs would not be acceptable to exceed the sum of one million Euro extra, resulting in a total alternative price of 3,5 million Euro. It was foreseen that any 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 specification (with a variation on the tubular structure and the cladding) and the alternative for the composite sandwich panels.

07.06 AMAZING SOLUTION!

Only two days after the tender closed a telephone call was received from the local representative architect Zachi Halberstadt, speaking on behalf of Moshe Safdie. He gave the compliment that the architect saw the alternative proposal as “an amazing solution”. Halberstadt invited for an immediate meeting in Tel Aviv the next day, so that the idea could be presented to the entire building commission. At this presentation the polystyrene models that Haiko Dragstra had machined in a demountable model scale 1 to 40 were shown. The models also proved that the corner details in the design had not yet been accurately designed and that the overall stability was not satisfactory. The design needed a considerable attention in the design perfection. But the enlarged scale model showed the seriousness of the tender.

The building commission was astonished after hearing the explanation of the construction and the consequential logistics of the alternative proposal. The five big wings would have to be constructed in one of the empty ship building halls in the Netherlands, like 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 top in order to apply the lower layer. The milling polystyrene machine had to be moved nearby this production hall and to be installed adjacent to the assembly area. After gluing the polystyrene blocks, the top skin could be applied. That is, if the polystyrene blocks would form a roof wing in horizontal position. After completion of the GRP top skin, the object had to be turned over and the bottom skin had to be applied. After the completion of the surfaces of the shells, they would be loaded on an open inland vessel and towed to the port of Rotterdam, where the cargo would be loaded on a specially chartered ship in which the 5 finished shells could be stacked vertically.

This ship would sail to Tel Aviv and anchor at sea in front of the city. From this location a giant freight helicopter 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. The whole shipment and air transport was pretty special and expensive. After explanation of the logistics of this alternative proposal, the 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.

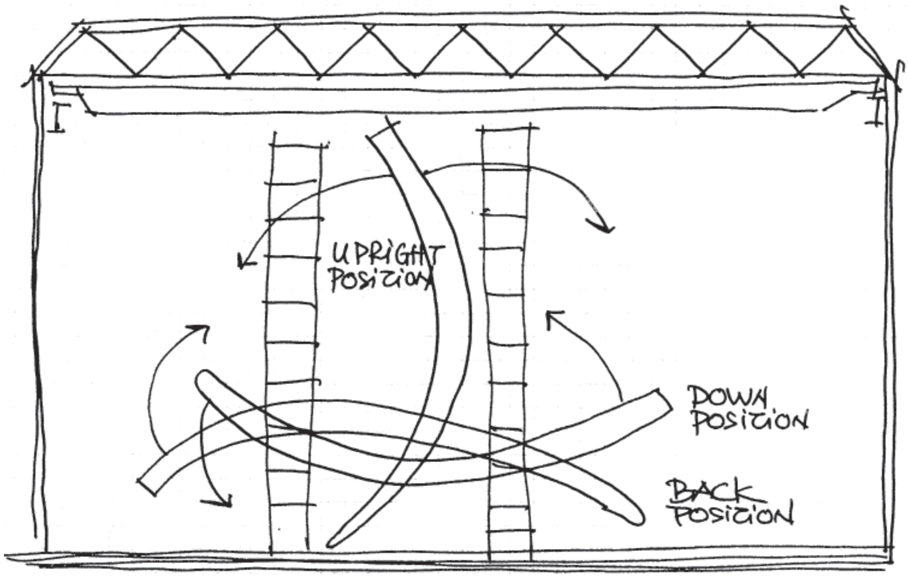


FIG. 69 Schematic drawing of a shipyard building with roof-wing positions

FIG. 70 A 'wing' transported by helicopter (photomontage)

07.07 EXTREMELY INNOVATIVE, BUT EXPENSIVE

The client's building commission went into a separate meeting. After one hour of fierce discussions, the outcome was that the tender original with the thin GRP covering was practically on the average tender price level. On the other hand they noted that the alternative proposal with the composite sandwich constructions was indeed very attractive from viewpoint of its extremely innovative design and construction, but was priced one million Euro over budget. By the way, from a selling point of view and knowing the intellectual value of the alternative proposal, it would have been stupid to sell it at a lower price than the tender proposals. 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. An 'avant-garde' designer also looses 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. But in the case of the wings, there was not a suitable technology yet in the world. The alternative idea was to become a technical world novelty and Moshe Safdie understood this. The discussion at hand with Safdie was about the Sydney Opera House (built in the 1970s) 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. Even though the realization of the Opera House meant a major step in the history of structural engineering. The Sydney Opera House, with its problematic realization, its time elongation, budget explosions, growth of Ove Arup Engineering and the architect's dismissal from the site, is now the most admired building of the continent of Australia. Through these discussions it was noticed that the marketing concept apparently had worked. Safdie appraised his belief in stating that he thought that the idea was amazing and never done before to his knowledge. If someone could make it work in his opinion, it was to be Mick Eekhout cum suis. 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 Euro. 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 29 April 2003.

07.08 RETHINKING THE ALTERNATIVE

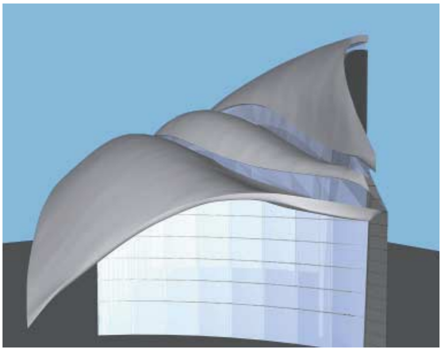
Back in Delft the consequences were discussed with the in-house engineers and the external consortium tender team members. The plan was born in the airplane from Israel to the Netherlands. If the GRP sandwich roofs could be realized, it would be a hit on the world market. It should be possible to transfer more labour to Israel in order to reduce costs and talk to new Israeli partners if the current partners would let the project down in order to realize this proposal. The first idea was to try to decompose the big wings into transportable components, which could be assembled on-site on a jig, smoothen the visual surfaces between the individual segments, to finish the outer GRP layers and give the shells a final top-layer or top-coat. Complot could machine the polystyrene blocks locally and Polyproducts could set up an Israeli GRP plant in Tel Aviv on the building site. The most likely position to assemble a wing would be in a vertical position. This way both outer skins on the polystyrene core foam could be treated simultaneously and the shrinking of the foam could be controlled. Subsequently, the roof wing could be easily lifted by a mobile crane from between two 20m high scaffolds.

However, after a few more 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. He had never exported his products and felt not comfortable in unknown areas. The bottom price of co-maker Polyproducts in Israel did not give much hope either. So the co-maker would think the world of the high number of innovations in this project and kept his price high. At the same time the usual squeezing of tender prices was set in, which forced the sales department to land on another price level altogether. For sake of financial negotiations, 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. To take an internal and hidden steel space frame with 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 still 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. A separate pre-engineering contract (or prototype development contract) was drafted for redesigning some steps on refinement of the roof models, and investigation in prototypes for different composition, to convince the makers themselves of the attainable quality and subsequently the architect and the client. After this decision the process went into redesign development and developing prototypes of segments of the construction of the Great Hall with the most complex wings, assuming that the details of the Library would follow those of the Great Hall.

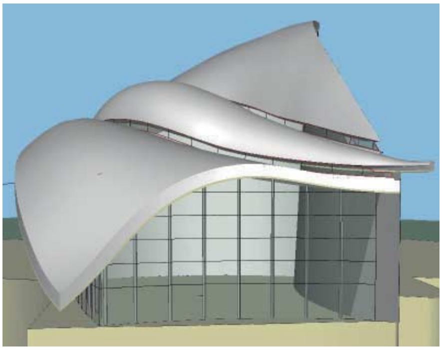
07.09 REDESIGNING, PRE-ENGINEERING AND PROTOTYPING

In the course of the design development of this first prototype development contract the redesign had to follow the rough contours given in the tender stage by the Safdie office. The official data of the three wings of the Great Hall were handed over by the architect's office as a Rhino scan from a material 3D model. The data within this model needed serious converting, since they proved to be inadequate and inaccurate for further engineering. Through analysis of different cross sections of the model and connecting these in fluent lines, a new and usable 3D model was developed. This ensemble was redesigned in another modelling program: Maya (3D CAD software). This software turned out to be an excellent medium for designing the different components. Also, the same software enabled constituent parts to be defined and combined into the total composition of the project: five sandwich roof wings, the steel columns, the three skylights and glass panels in the 4 glass facades. It became unavoidable in this stage that the final contract had to include also the reinforced concrete walls as well as the support plates of the concrete tops for anchoring of the columns, as the particular geometry of the roof wings would determine the concrete work below, although this concrete work was part of the main contractor's lot.

At the same time a global structural analysis was made of the structural behaviour of the GRP wings and the steelwork. During this time the two quoted construction types were both worked on: the original version of a tubular steel structure of systemised CHS circular sections, covered with a thin GRP sandwich as the roof covering and the alternative designer's option of the structural sandwich composite structure. Sales negotiations with the client had resulted in an unavoidable change on the purchase side of the co-maker for the polyester work. The price of Polyproducts was remained stiff on a too high level and they were terminated as a co-maker in the process. Holland Composites Industrials (based in Lelystad, NL) was invited as the polyester co-maker in their place. They had previously made hulls of motor yachts and sailing yachts in glass fibre reinforced polyester (GRP) up to 30m length with the vacuum injection method. This was an excellent starting point for the development of the structural sandwich panels. They employed the firm Solico Engineering (based in Oosterhout, NL) who started to globally analyse the GRP roofs. The two structural analysis of Octatube and Solico were compared and matched.

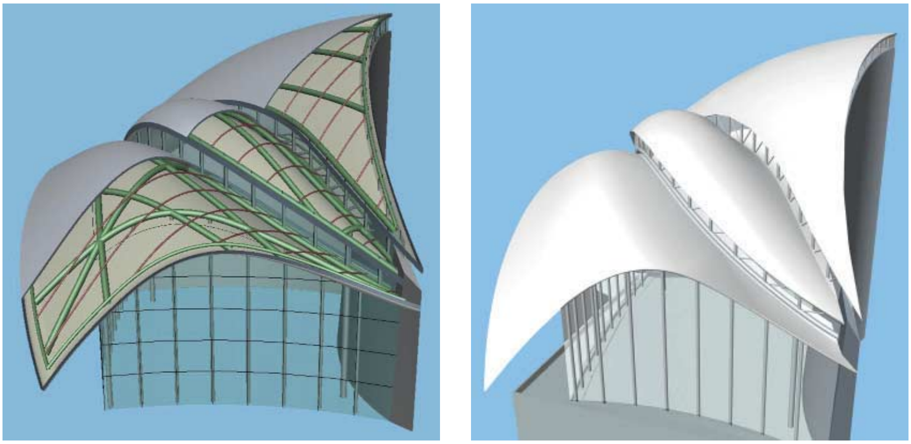


1



2

FIG. 71 The Rhino model of Moshe Safdie & Associates and the first redesign in Maya by Octatube.



1 2

FIG. 72 Two construction types: a steel structure of CHS circular sections and the structural sandwich structure.

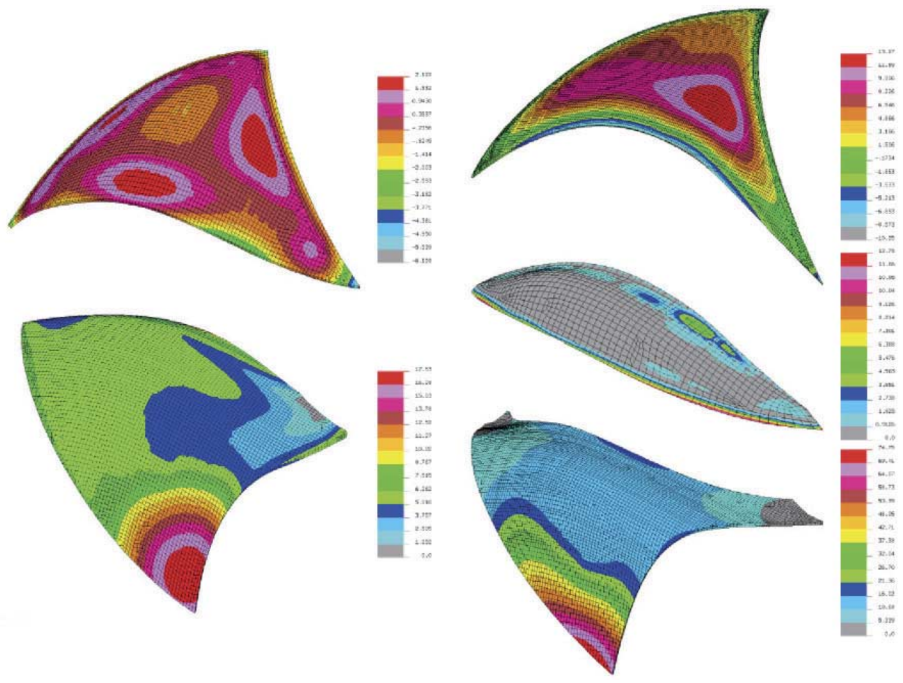


FIG. 73 Structural analysis of deformation of the GRP sandwich roofs made by Solico. Left, the upper and lower wing of 'The Library'. Right, the upper wing, the central body (made of steel with a GRP covering) and the lower wing of 'The Great Hall'.

At the same time, prototypes were made of both construction types: the tubular steel structure with a light composite sandwich polyester covering and the alternative designer's solution of the integral composite sandwich. Both prototypes were shown to architect Moshe Safdie, together with the first results of the Maya computer redesign work in July 2003. In the mean time this pre-engineering work had indeed resulted in a dramatic reduction of the cost price as the engineering team became more and more familiar with the experimental aspects and how to resolve these. The original quotation was reduced to around the original average price level, thanks to the results of this pre-engineering contract. So the pre-engineering contract, as it was seen by all involved in the process including the client, was a wise decision. Such pre-engineering prototype contracts are often proposed for experimental projects in the Netherlands, but hardly ever rewarded. The effect is that both sides are getting accustomed to the characteristics of the experiments at hand and that the makers loose uncertainty, which would result in adding high contingencies in the global price. Clients mostly refuse these pre-engineering contracts out of fear for monopolisation of the involved contractor. In that case the client could also have the architect undertake such a prototype development contract with restricted legal conditions. And indeed, monopolies are almost a natural consequence of specialization.

07.10 RESULTS OF THE PROTOTYPE DEVELOPMENT

The course from redesign, pre-engineering and prototype development to final design took one year involving 5 to 6 engineers. The architect visited the development laboratory in 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 Blob structures at the engineering department, there would only be one party involved with computer work. In this case the engineering department would be in the lead and the architect would only supervise and give instructions behind the monitor. It would also put the legal responsibility on the same table as the technical development responsibility. The impulses from the development of the prototypes, the production methods involving moulds and injection production plus the future assembly of the structural seams and the structural behaviour of the total wings, all had a deep impact on the final design and had to be fixed by the responsible 'design and build' contractor. The described innovative developments followed the three axioms of the contractor: "Design and build in one hand", "Integration of architectonic, structural and industrial design" and "Development of new and experimental products". Respecting the wishes of the architect an intensive design and engineering course was followed mastered in the engineering department, co-ordinating Holland Composites and Solico Engineering as indispensable co-makers. 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 course with multiple degrees of innovation. During the entire process the design methodology as development for special components, consisting of 3 mains phases:

- Design Concept,
- Prototype Development,
- Production Preparation,

as published by Eekhout [2007] were followed quite literally.

07.11 TECHNICAL ENGINEERING AND PROTOTYPE TESTING

After the first one year of experimental work and prototyping, the final 'design & build' contract was agreed on the basis of the adapted quotation and the approval of architect Safdie on the quality of the prototypes. The final engineering started on the basis of AutoCAD and Mechanical Desk Top. The final analysis incorporated:

- Final production methods of the GRP wings;
- Testing of the connections of the sandwich panels on de-lamination;
- Assembly connections loading deformations;
- Fire resistance;
- Logistics in the Netherlands;
- Transport of the sandwich segments in special open containers;
- Assembly of the segments on special moulds on the building site;
- Jointing and finishing the wings;
- Hoisting of the completed wings into position.

After the prototype development phase of the first one year the final engineering inclusive prototype construction testing in the laboratory also took one full year. At the Israeli side approvals became very complex, however. Due to political change in government from the Labour party of Rabin to the Likud party of Sharon, all proposals were reviewed by the local government bodies with extreme attention, so that many unforeseen and sometimes unnecessary problems were detected by the governmental bodies and had to be neutralized by the engineering parties. Many people in Israel apparently did like to see the project uncompleted or stopped half way. This 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, prof. Adriaan Beukers and prof.dr. Michel van Tooren, who played an inspiring role in the Atomium recladding project, as mentioned in chapter 4. They were invited by the client [The Friends of the Rabin Center] directly to draft a second opinion on the supplied engineering and played their role in this project honourably.

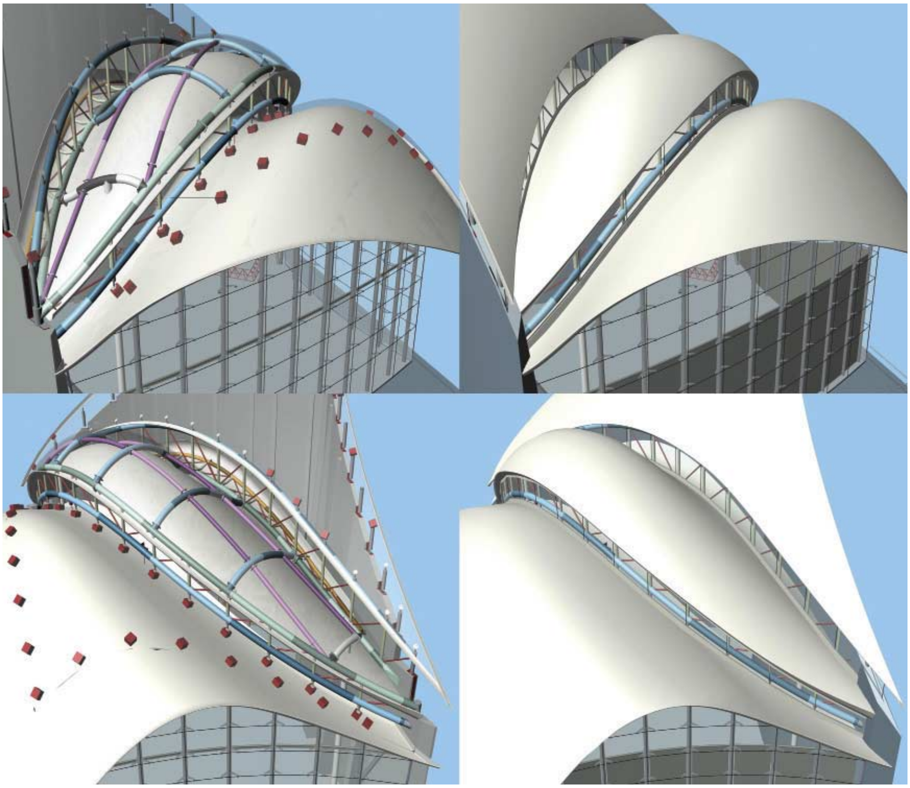


FIG. 74 Close-up of 'The Great Hall' wings with insert points for connectors to connect the wings to the columns and structure of the 'central body'.

07.12 PROTOTYPING, PRODUCTION AND INSTALLATION

After two years, in January 2005 the go-ahead was given for production. From that time onwards the production of the composite segments went into operation. Hence the third project year of production and assembly started with the experimental production of the components on the negative moulds. It was decided that production would start with the smaller roof of the Library, although the client had in the back of his mind only eventually to build the Great Hall, just in case the costs of the sandwich construction operation would be too high. So seen from the learning curve in the production development, the very production of the two smaller roof wings of the Library was taken up first.

The production technique used in this case has been taken from standard production techniques of producing sailing ship hulls as Holland Composites had produced its integral mono-hull ship hulls. The base of the vacuum injected production was a good point of departure. In case of the sandwich wings the second dimension in the largest wings of 30 x 20 m (compared to the 30 x 5 m boat hulls) and the impossibility to sail the completed wings independently to the site like a sailing ship, proved to be a major experimental level for the GRP production. It was decided that the entire wings would have to be produced in more or less rectangular segments, to ship them out stacked in containers and to assemble them in the form of the completed wings on site and hoist them in as wings finally. This had as a consequence that the segments had to be produced individually in their deconstructed shape of one-off forms. Each segment form was different. All segments had a different form and some had long asymmetrical points. The shrinking of these segments after curing of production proved to be an unforeseen adventure. Shrinking of each segment appeared asymmetrical, always in another direction and during production one could wonder how all of these twisted panels could lead to a smooth form.

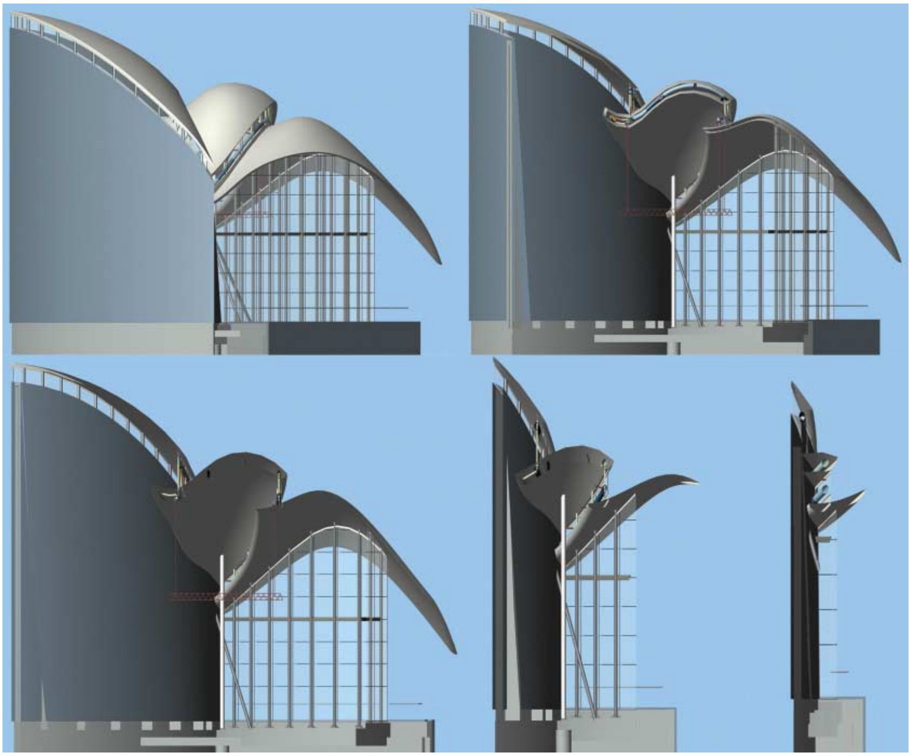


FIG. 75 Five sections of 'The Great Hall'.

Unusually for the co-maker the production proved to be necessarily very engineering intensive. The foam blocks of polystyrene had been milled accurately by Marin bv, specialised in moulding ship models for hydraulic testing, to negative moulds from CAD/CAM files. After 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 fibre is impregnated with polyester resin by sucking the plastic envelope around the fibre weaves and foam core blocks vacuum and by feeding polyester from the other side to enter into the cavities of the construction: in the fibre weaves and between the foam blocks. Since the resulting layer of GRP at the mould side describes the desired form of the roof in the best possible way, this side had to become the upper layer of the roof. From the prototypes it was concluded that the segments had to be produced top down: the upper 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 all regularities would ruthlessly be visible. Less so on the lower side with its 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 flush. The fire proofing tests resulted in an extra internal layer of gypsum rich finish, which would heighten the fire proofing characteristics of the inner face of the wings to the required level. This implicated that the inner face had to be smoothened after assembly any way. So production with the upper surface at the mould side was the consequential procedure.

It was also decided to pre-cure the top layer as a single layer of fibre weaves with polyester resin before vacuum injection of the complete package of the segment construction. After the top layer of resin soaked fibre was cured, the core of fire-resistant polyurethane blocks was sawn and arranged to the roof layer. Between these foam blocks long glass fibre strips were placed in vertical position to act as stringers between the upper and lower skins. These stringers are the structural ribs in the sandwich as a replacement of the original steel structure or as a stiffening of the sandwich composition, which appeared to have too much flexibility for the roof structure. Tests and analysis had resulted in the introduction of these stringers to lead away the shear forces in the construction package. Due to results of the performed accelerated long time tests delamination could occur at the most critical points: at the supports of the columns, between the internal spans and the cantilevers. A similar problem and loading occurs at the attachment of an airplane wing to the fuselage. The core foam blocks were subsequently covered with the lower set of glass fibre weaves to form the bottom skin of the segments and an enveloping foil for the next vacuum-injection. The polyester resin that was consequently injected between the blocks, forming the GRP glass fibre strips stringers, thus creating a structural connection between the upper and the lower skins.

In doing so the function of the core blocks had dramatically changes. From the original shear layer, they were now only functioning as ‘lost internal moulds’ for the lower surface of the wings. Its function was also foreseen as a stiffener of the upper surface to ensure that a solid backing is available behind the upper skin if an unfavourable local load was to occur on the outside of the upper roof skin. Local buckling of the GRP sandwich is prevented in this set-up. After production of the first three roof segments of the Library, a mock-up was installed at the premises of Holland Composites. The segments were placed on a temporary supporting jig structure in order to fit all the segments, to connect them structurally and to smoothen the final layers in order to prove to the manufacturing team, the engineers , the architect and the client respectively that the wing-shape would have the desired fluent shape without any irregularities. This mock-up was built in March 2005. After a site visit of the architect, and with his approval, 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, around the time of the first congress of Delft Science in Design, the two wings of the 'Library' were shipped to Israel in specially designed super-crates, sized 3,5 m x 3,5 m x 15 m in volume to contain as many segments possible in stacked position in a specifically designed order. Transport was foreseen in 5 lots of the 5 different wings via regular freight ships to the harbour of Ash Dod and from there on to the site by inland trucking transport. Parallel to the production of GRP segments in Lelystad, the production of the steel columns and the rotating column heads had commenced in Delft. Next to the load bearing function towards the roof these columns also bear the deadweight and wind load of the frameless glass façade. Production of the columns appeared to be a routine job, the only difficulty being the connection between the columns and the roof. All columns had different 3D angles and the sandwich construction was quite weak on the positions of the supporting columns so that a danger of punching the column supports through the sandwich was analysed. Hence during the production of the GRP segments at Holland Composites steel plate inserts parallel to the lower surface of the wings were placed within the sandwich to be able to connect the steel upper plates of the ball joint column tops to the sandwich construction without perforating the wing. Specially developed ball-and socket-connections on top of the columns were designed to accommodate the very different corners of the supporting points under the lower skins of the wings. The ball joints had to be bolted to the inserts.

A large challenge for the steelmakers proved to be the central body: the central part of the 'Great Hall'. Due to the large forces from the upper and the lower roof wings amongst others, this part of the roof has to cope with, unfortunately a tubular steel space frame was the only solution to make this span under this loading possible. The result was a complex space frame structure of tubular steel, later to be fitted with thin GRP panels at the top (roof surface) and bottom (ceiling surface). Because accurate 3D rolling of tubular elements is a rather complex procedure, the entire composition was made in 2D rolled tubular segments, which possessed a greater accuracy. The 3D tubes, mainly situated in the length of the central body, at best approaching the desired shape, therefore had to be connected to the accurately shaped 2D tubes. At the premises of Holland Composites the entire central body was assembled in order to fit the panels. The structure appeared to be as high as 8m, which was very labour-intensive for the erectors. So after the trial assembly in Lelystad, it was decided to build up the final assembly on site in Tel Aviv in two halves, which would result in a building height of only 3 m. After the panels were trial fitted on the particularly engineered and positioned stool supports, the structure was disassembled en transported.

FIG. 76 Milling machine at Marin, scale model of upper wing of 'The Library' and 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 GRP,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. Final result, in this case an early prototype. Discarded foam moulds.

After the production of the roof segments of the lower wing of the Library, discrepancies between the theoretical drawings and the practical distortions and tolerances from shrinking of the polyester resin in the enveloping vacuum bags were measured. Tolerances because of warping of the negative moulds resulted in unforeseen deformations of the produced GRP components. These components together had to form the ruthless smooth surface of the complete wing in the end. All aspects were approached in an engineering manner: measuring, analysing problems and deducting solutions. Analytical engineering in the best traditions of the TU Delft made the initial amazing, improbable design solution finally a reality. The resulting design is a combination of structural design with a strong architectural flavour, incorporating the technologies from aeronautics, ship building, industrial design and geodetic surveying. It poses an example of multiple innovation of technology.

FIG. 77 The central body of the Great Hall (spanning ca. 30m).

FIG. 78 Detail of the central body.

FIG. 79 Roof segment of the lower wing of 'The Library'

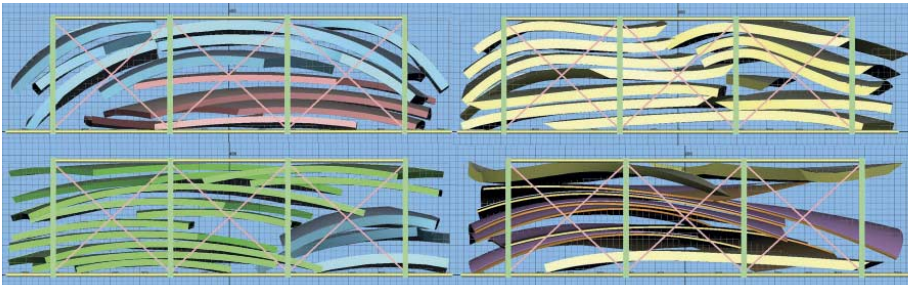


FIG. 80 3D drawings of the roof segements in 4 special transport containers

FIG. 81 Building site in Tel Aviv zoomed in on 'The Library' with the truss and columns already installed.

FIG. 82 Open container at Holland Composites with the roof segments ready for shipment

07.13 ASSEMBLY, TOLERANCES AND THE NEUTRALIZATION REGIME

Due to the experimental character of the production process and the initial unfamiliarity with the consequences of vacuum deformation, it was decided to perform a test-assembly or pre-assemblage on the premises of Holland Composites in Lelystad of all the wing segments. The fitting took place on a positive steel frame, the shell would therefore be curved upward. One of the conclusions was that we would assemble the wings inversely, so the downward curve would face upward. When a technician would fall, he would fall in the shell, instead of falling off the shell. Subsequently the shell was turned over with a mobile crane, by means of three temporary hoisting fixtures in the shell. From the pre-assembly conclusions could be drawn regarding the theoretical versus the practical measurements of the individual segments. All segments were produced on individual foam moulds and they all had their own shrinkage and shrink-direction. Yet together, these segments were required to form the unforgiving smooth surface desired by the client and architect.

It was noted that the total fitting of the individual deformed segments would still form a smooth surface when the entire shell was assembled. In order to acquire this smooth surface a solid frame was needed with clamps in order to force the segments in the desired position. In general the segments proved to be somewhat smaller than intended. They had shrunk because of the vacuum injection, causing the seams to be 20-25 mm, instead of the anticipated 12-15 mm. When filling up the seams during assembly a bigger seam meant more fibre and more resin (due to the required ratio between fibre and resin) and thus causing a larger weight of the shell.

The connections between the individual segments can be divided in connections in the length and connections in the width of the segments. Both have a structural function. On the side of the segments a rabbet has been made of 220 mm with and 15 mm depth. In this rabbet a prefabricated reinforcement strip of 200 mm width and 10 mm depth (of high density glass fibre weave layers that had been vacuum injected with resin) was placed. This reinforcement is glued and clamped by screws for curing purposes only. After the segments of the two wings in Lelystad were fitted on the steel frame, controlled and approved, the segments were dismantled and shipped in the special containers. The assembly on site had to take place on the south side of a tall wall on ground level. The segments were assembled inversely, measured, connected by the prefabricated reinforced strips, measured again, touched-up and finished with the structural reinforcement meshes and filler. The lower side with a fire retarding layer, the upper side with a infrared light resistant layer. Next, the shells were turned over and identically finished on the other side. After the hoisting onto the Library, the first shell wing was positioned on a steel flat truss sub-structure, which in its turn rested on a concrete wall with a much larger tolerance difference. Positioning directly from the crane onto the column heads, or wing-connectors with its adjustable shaft and connection plates, could only take place accurately by following the theoretical drawings. Until the end of the assembly and erection theoretical drawings remained the decisive factor. In all phases of engineering, production, assemblage up until the hoisting and positioning theoretical drawings were always present and compared, as this was the only assurance that at the end the wings would fit into position. Neutralizing different components is a adventure in itself. Building parts were simultaneously produced in locations all over 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 works in Tel Aviv. The concrete had the biggest tolerances, up to 100 mm. The seams of the roof segments measured theoretically 12 mm, in reality 25 to 30 mm and the seams between the glass panels a more accurate 8 to 12, average 10 mm. And all these different tolerances have to be neutralized in their principle detail design (allowing neutralizing at all). Tolerances in the different stages from design, through engineering 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 Blob structures for Free Form architecture had to be realized. Having arrived at this point, one has to remember that the success of Henry Ford in the automotive industry was not the conveyor 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 manufacture, 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. Rather it was 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 with 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 the costs were as much as 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 many countries all over the world for just one project, put the building industry in line with the automotive industry, only 100 years later. This is helped by the change-over from the concrete and bricks technology where joints always can be adapted locally, to the more industrial (factory manufacturing) metal and mid/high-technology where all components have to be fitted specifically in an industrial mode, so with outspoken and very accurate tolerances only. Once Henry Ford could force his components 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). This made the difference between the former automobile ateliers where cars were hand-fitted after most of the time was lost in refitting the components and an industrial and almost 'blind' assembly only focussed on the assembly activities and not any more on the component care. From that moment on, Ford could even employ a conveyor belt as the continuous production base of assembly-only. The glass facades were developed separately from the roof wings. They 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. The architect required a specially fitted glass in order to influence the daylight penetration and the solar entrance. This part of the building was not as interesting scientifically.


1


2

FIG. 83 Assembly of the roof segments by gluing and bolting glass fibre polyester plates on the seams before applying the finishing layer.


1


2

FIG. 84 Preparation and hoisting of the upper and lower wing of the Library in August 2005.

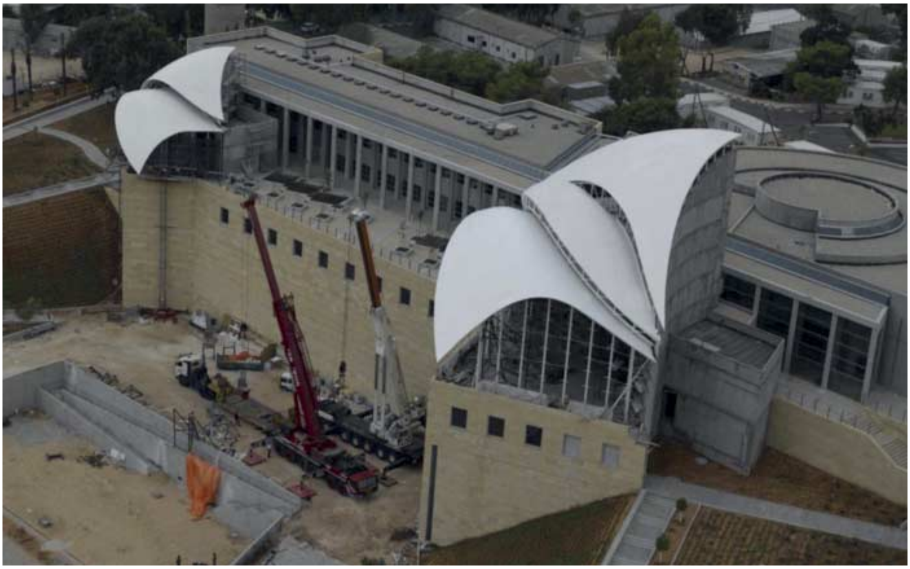


FIG. 85 View of the building site on the 6th of November 2005, photographed by Ardon Bar Hama

FIG. 86 Overview of the building site after completion.

FIG. 87 Interior view

FIG. 88 Finishing of the top layer of the roof by "airborne builders"

07.14 CARBON FIBRE BLOB SHELLS, AS YET ONE BRIDGE TOO FAR

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 hyperboloidal forms. Results were mostly 50 mm thin concrete shells with only one central reinforcement layer of steel bars. Many shells had an Hispanic origin: Eduardo Torroja, Spain, and Felix Candela, Mexico were the prominent pioneers. The shells were built in countries with high material and low labour costs. In the 1970s the pioneer's retired and the concrete shell fashion stopped. Crafted carpenters retired after that and nowadays making a concrete shell would again become an experiment. Heinz Isler from Switzerland built his concrete shells with re-usable timber moulding on scaffolding in the 1980s. He also retired and closed his company. These concrete shells have now to be designed in open en direct collaboration between architect en engineer.

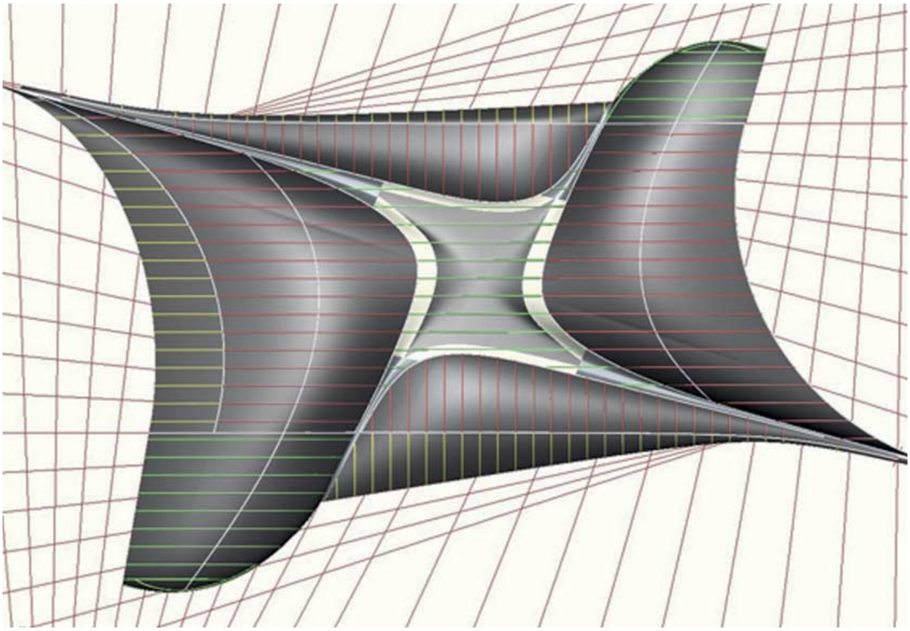
Blob architecture emerging in the late 1990s (Guggenheim Museum Frank O. Gehry, 1998) changed these conditions, as the architect designs either directly in models or on the computer as if he is a sculptor. The dramatic 3D effect dominates architectural thinking. The structural designer has not an equal position, but is asked subsequently after the architect has found out a model or geometry, which suits him out of visual design considerations. Alas there are usually no direct feedbacks, no improvement feedback loop from structure to architecture. That is to say the engineer has to realize the sculptural whims of the architect to a trustworthy architectural structure, safe in use. This has as a consequence that the form of the new generation of shells are much more arbitrary in structural sense and hence have a more unfavourable structural behaviour.

Many of these new shells are now governed by bending moments due to their unfavourable form and supports, rather than by normal forces and shear forces in the plane of the shell as in the first generation of shells. The constructional solution of the new generation of composite shells is in principle the one developed for the Rabin project and now the system solution: a double stressed skin sandwich composite construction in free form with a structural core. The two skins enable bending moments to be taken, caused by unfavourable loading conditions, column or support positions and, structurally speaking, arbitrary or rare shell forms. We would still call these roof forms 'shells' as a reminiscence to the thin-walled shells from the 1960s, but mathematicians and methodologists suggest to invent and publish a new name. The answer is: Blob-shells of Free Form shells.

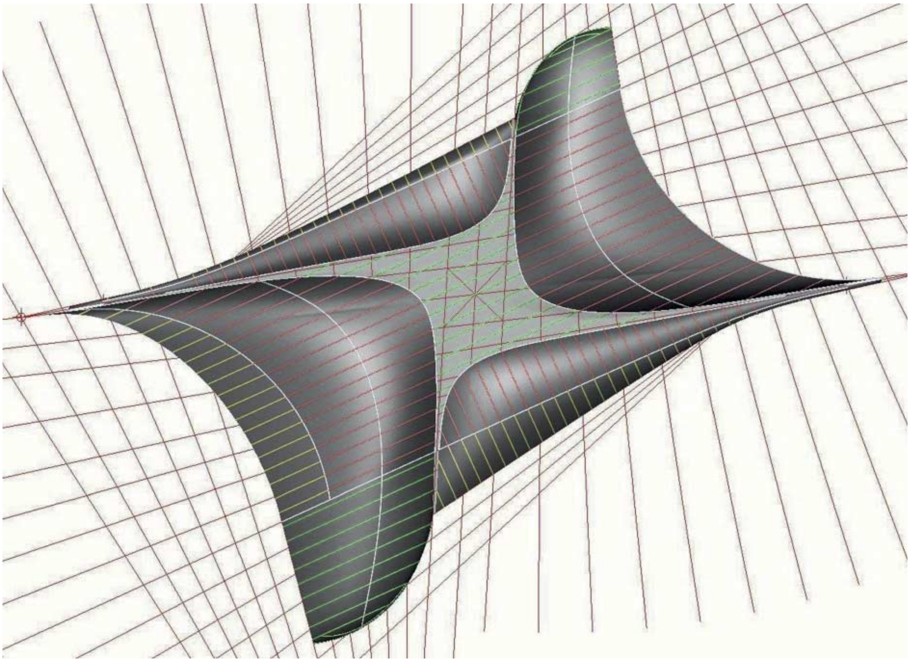
The next step in development is caused by the differences in loading behaviour between conventional structures in steel of concrete and glass fibre reinforced polyester shells. Blob shells, made of glass fibre reinforced polyester are usually much more flexible, and cannot reach the stiffness and rigidity of conventional structures.

07.15 FROM GRP TO CARBON FIBER REINFORCED EPOXY

For sailing yachts, often pre-stressed by its masts and riggings, rigidity is a relative connotation. As long as the doors and cupboard 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 vulnerable, annealed 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 the engineer's attention. Cantilevering blob-shells are more flexible than in conventional structure. The cantilever of the tip of the largest wing at Rabin was analyzed as 100 mm upwards and 210 mm downwards. The total sandwich thickness was 314 mm. This fits in the general shell theory of Timoshenko, so that this composite shell still behaves as a shell. Alternatives in steel and in concrete were analyzed to show deformations of 200 respectively 100 mm only. The engineering line-of-thought was that, as long as the movements of the roof under loading do not cause brittle fracture, de-lamination or other handicaps in the blob-shells internally 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 movements in the silicone joints, a larger movement would be acceptable. So no rules yet, but intelligent and responsible building technical engineering, characterizing the experimentation phase. The standardization and normalization phase of newly developed technologies will follow after 5 to 10 years only. But new projects involving blob-shells in future will show up with no doubt more strict requirements as to the anticipated deformations in GRP. Other materials are interesting in this respect as well. Epoxy and carbon fiber is the alternative usually employed in the production of high-tech sail yachts. The next generation will probably be blob-shells in carbon fiber reinforced epoxy. This material is much more rigid, does hardly expand as the modulus of elasticity of carbon fiber reinforced epoxy is much lower than that of glass fiber polyester. However, these advantages are accompanied by a much more strict production process including curing in a tempering oven, which limits the sizes of components. For transfer of technology from the yacht building industry (for example used in the black and white ABN AMRO yachts of the 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 building 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 celebrated, the second one is a looser. 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.



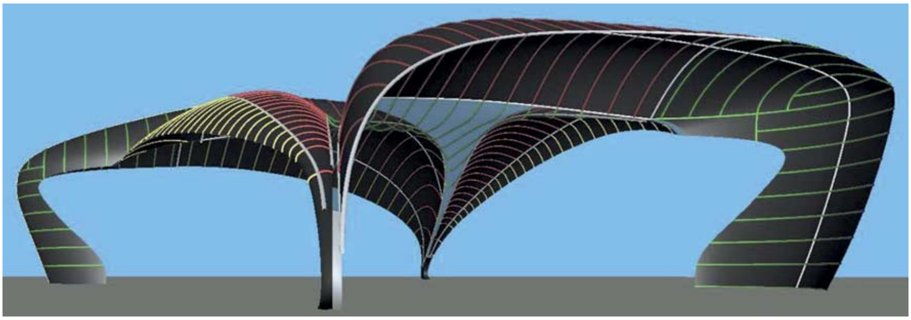
1



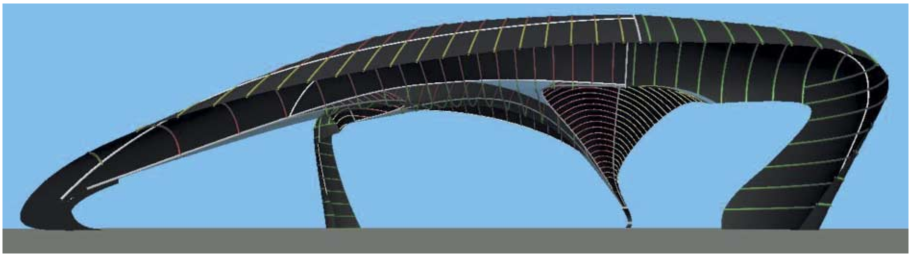
2

FIG. 89 Plans of the roof of the Mediatheque with subdivision of components

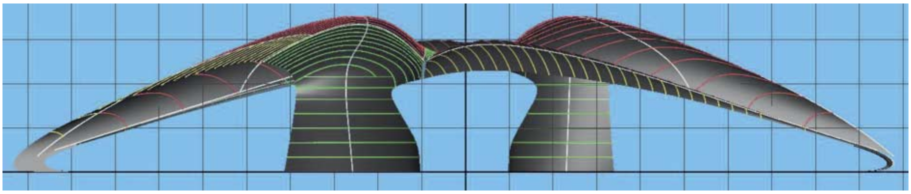
Her initial design images show the 'Mediateque' in white, but the tender documents of 2005 show now a black design with carbon fiber as the basic material. In the development of the Mediateque tender design in the proposal of the author, accompanied by co-makers in the Netherlands and England, the idea was production of the segments of the carbon fibre epoxy blob shell segments locally in a temporary factory shed, a re-assembled curing oven, next to the site. The process of tendering did not allow for any prototyping on the side of the client or architect. Rather this extremely experimental project was tendered as a standard building project. The resulting tender price was 4 times that of the client's budget and, may be as 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 '8ième Grande Project' died the day before the tender date. The project was cancelled. The town was relieved. The design drawings indicate the design proposals in carbon fibre epoxy blob shells, which will probably be illustrated in a next Delft Science in Design conference at TU Delft if the experimentation course could be continued.



1



2



3

FIG. 90 Elevation drawings of the Mediatheque in Pau by Octatube

07.16 CONCLUSION

The resulting design in this contribution shows that building technical design can lead to an integrated and innovative process. In such processes many disciplines are collaborating and have to be co-ordinated throughout the entire process inclusive all of its unforeseen and experimental stages. The results of this process have to be integrated into one technical artefact that satisfies all requirements and gives efficient answers or compromises in all of its life phases, be it conceptual design, material design, detail design, engineering, productions, assembly, installation, loading behaviour, functional use as a building, meaning of the artefact as a building, (even as Architecture) and in its (global) context/surroundings, in its meaning as integral part of the building.

Society expects perfect solutions from scientific designers. These solutions are not only the functional and technical solutions. It may be true that the well-known restrictions in the volume prices of the building industry, as posed by the clients in the building industry, lead to traditional and well-known technologies. Yet the thresholds to enter the building industry are low and competition is fierce. Sometimes experiments are persistent, initiated by technical designers who are willing to wander though the entire experimental development process and are able to analyse and solve all foreseen and unforeseen problems. It requires an experimental mind set.

In this case the interdisciplinary collaboration from Architecture with Industrial Design Engineering, the Maritime Engineering and Aeronautical Engineering proved to be essential and an enrichment in the field of Architecture in order to introduce the renaissance of the shell as 'Blob shells' of 'free form shells' for the world.

The content of this chapter has been extended in a book 'Lord of the Wings', written by Mick Eekhout and Sieb Wichers, published by IOS Press, Amsterdam 2015, ISBN 9781614995494.

REFERENCES

REF. 07.01 Beukers, A., (2003), Licht. lichter, lichtst: lichtheid als gedachtegoed, Delft.
REF. 07.02 Eekhout, M., (2007) Product Development and Component Design, Multi Science Publishing, London
REF. 07.03 Kohn W., Rowe, P., Rybczynski, W., Goldberger, P., Sorkin, M., (1996), Moshe Safdie, Academy Editions, London
REF. 07.04 Tooren, M. van, (2003) Sustainable Knowledge Growth, Delft.
REF. 07.05 Womack et al, (1996) The Machine that Changed the World, Harper Perennial, New York, ISBN 0060974176

08 MORPHOLOGY FOR NON-ORTHOGONAL HIGH-RISES

Karel Vollers

Non-orthogonal high-rise buildings are emerging with an increasing degree of geometrical variation. As yet no scheme categorises data on the basis of the overall geometries of such buildings. The author proposes an easily accessible morphological scheme which for example, enables data to be retrieved on sustainable performance of the distinctive building shapes. The shaping of most non-orthogonal high-rises is related to developments in modeling software. The morphological scheme is based on software manipulations to describe shaping, not on mathematical formulae. As software develops, new ways of generating and new shapes emerge. In consequence the shaping scheme gradually will be updated. The scheme is illustrated by examples of overall shaping and materialization trends.

08.01 NON-ORTHOGONAL HIGH-RISES

Iconical buildings express regional or national identity. They symbolise power and ambition. This built identity, created by mankind, is highly valued and of major importance in global communication. To design outstanding buildings, architects move away from the standard. Shapes of simple geometry are increasingly varied on to add expression. Designers get accustomed to applying complex geometries, and refine the shaping.

Sustainability of high-rise is questionable, but for political, cultural and socio-economic reasons, they are built in large numbers. As boxes and as curved volumes. Curved volumes especially in high-rises offer economical and sustainability advantages. A very efficient floor/façade ratio is attained by bulging the volumes and rounding the contours. This implies less building material, maintenance and energy consumption. Also as to windage, curving a high-rise volume often is profitable. Windage of a 90° twisted building is 40% less than of a cube-shaped building of the same floor area. It implies a lighter superstructure.

The budgets of iconic projects push industrial innovation to meet the new shaping and the quality demands to guarantee extra-long building life-spans. The growing market of non-standard curved products, stimulates application of strong curvatures. Iconic articulated buildings in the mid-rise range of 60-100 m have started to fill the gap between slightly curved high-rises and strongly curved low-rise buildings.

08.02 MORPHOLOGICAL SCHEME FOR HIGH-RISES

Integration of digital technologies into the various stages of building development is resulting in a variety of high-rise volumes with curving façades. Their geometrical complexity is increasing rapidly, and by implication the complexity of materialising. An easily accessible database that distinguishes according to overall shaping, will be useful when optimising build-up and performance of high-rises with curved façades. The author found no database nor morphological system matching the geometrical variety. Mathematical descriptions that qualify façade surfaces as being anti-clastic/synclastic, single- or double-curved, do not describe overall building shapes. Mathematical definitions of curved surfaces like hyperboloids, conoids, etc. are too difficult for most building participants to understand and do not sufficiently reflect the variations in building shapes.

A topology classification system designed by architects is described in Phylogenesis [FOA, 2003]. It schematises surfaces – not building shapes. The scheme requires too much study to be generally used in the building industry. In his book Skyscrapers-Skycities [JEN, 1980], Charles Jencks classifies by form and expression. A grouping by metaphorical equation [in skypricker, skyscraper or skycity] is elaborated with ambiguous and subjective names. He also lists the topics Morphology, Articulation of surface, Style, Activity, Technology, Motivation. Only the Morphology section deals with geometric descriptions. It subdivides into Central, Longitudinal and Compound buildings.

The section Longitudinal, classifies high-rises as a slab, stepped-, curved-, shaped-, amorpheus- or complex slab. It covers high-rise shapes in general, but does not determine variations in buildings with curved façades. Up-to-date high-rise project information is available on the website www.Skyscrapercity.com, at this moment the main website forum. Its database classifies according to geographical location, height, usage, etc. Not to geometrical shape. The morphological scheme proposed by the author deals with the overall shaping of volumes with curved façades. Compound buildings, i.e. those consisting of segments of different geometry types, are only briefly discussed.

08.03 MODELING SOFTWARE AND HIGH-RISE SHAPING

High-rise shaping is largely related to the modeling tools that architects have available. Simple modeling procedures enable intuitive shaping of complex geometry designs. Little mathematical insight is required, but the consequences for structure, usable floor-space, etc. are considerable. Designers are assisted by software in handling such data. Some focus on parametric modeling of the overall volume, others on morphogenetic structures, textures, etc. The relative ease by which one can design, allows rapid shape development and quick generation of digital data on components. The parameters can be manipulated numerically, and by adjusting points on the screen operated by mouse-clicks. In the first generation non-orthogonal building shapes, volumes were mostly geometrically described by manipulating straight lines or flat surfaces using the commands Copy, Move and Rotate (VOL, 2001). The process to describe non-orthogonal volumes involved handling large quantities of data.

In the second generation non-orthogonal building volumes, solid modeling software was applied. In such software, shapes are described by relations between their composing elements. Scripting and parametric modeling procedures greatly eased drawing procedures and processing of data. Control of freely curved surfaces built of, for example, Nurb curves is maintained by manipulating only a small number of points. In solid modelling software, volumes can be transformed by commands like Shear, Twist, Scale, Unite or Merge. The third generation non-orthogonal high-rises reflect the use of the before mentioned tools, but a sequence of their use is hard to distinguish. By scripted procedures, new shapes are generated with increased complexity in geometrical build-up. Designs often appear monolithic, with freely curved surfaces, textured by patterns of holes, ripples, etc. The complexity of their materialising, is anticipated by second generation building geometries that each were transformed with only a few tools. An early version of the scheme, grouped façade geometries by the chronological availability of a small selection of tools and software. Additionally, the popularity of twisted volumes had lead to incorporate features of their superstructure. Growing use of other geometries inspired to classify more high-rise shapes. To avoid ambiguity, the CAD-tool 2.0 morphological scheme, as the new version is named by author, only distinguishes volume geometries.

08.04 INFORMATION EXCHANGE BY GRAPHICS

The scheme is based on the observation that most high-rise geometries are primitive shapes, transformed by a limited number of manipulations. Mainly because of esthetics and building economy, the number of parameters used, generally is less than 4. As an example, most twisted tower designs are generated by scaling a cube into proportion, and then twisting the volume. Most people can easily mentally visualise subsequent transformations. Computer commands thus replaced mathematical formulae to indicate the form build-up. Manipulations may be depicted by icons and these may be supplemented with numerical information. Such representation resembles the way software parameters are depicted on computer screens.

NOMENCLATURE

To function optimally, the proposed scheme methodology and type names must find general acceptance. Hereto the scheme's names originate in widely used geometric descriptions of volumes (sphere, cylinder, cone) and in transforming commands (extrude, rotate, twist). Many command names resemble those in the tutorial book Architectural Geometry [ARC, 2007] and in modelling software of Generative Components and Rhino. With software evolving, for a similar command a different name may come into use. This changing of names is confusing, but sometimes is necessary to connect to new insights into form generation or to use of other or updated software. As shaping diversifies with new tools, more typologies emerge and new names will enter the scheme. Shapes can be generated in various ways, and by use of a variety of commands. Such parallel options imply that a volume can be classified by various transforming commands. A sphere, for example, may be selected directly as a primitive shape, be made by rotating a half circle around an axis or be generated by scaling in a modeling script a circular plan as it is moved upward. By listing these commands in an order of importance, more unity in use of names is achieved. When a choice between listed commands is possible, then the preferred adjective for a primitive, is the first from left. As other shaping procedures may come into use, other adjectives or a changed sequence, may become more fitting. When parameter values vary, for example the degree of twisting and scaling, or when a large series of transformations is applied, then the overall image often loses optical inner consistency. Most people will not understand how it was generated. When the sequence of manipulations is not obvious, or when the form does not fit in a category, then the volume is classified as a Free shape. (Names allotted by author are written in Italics). Special categories discriminating by function, composition or formal characteristic, supplement the scheme of overall shaping. These relate, for example, to wind energy or bio-climatic aspects. Specific features may also lead to adding descriptive adjectives to a shape name, such as Arched or Perforated.

EXAMPLE OF GENERATING A HIGH-RISE VOLUME

The 396 m high Oktha Gazprom tower (Figure 91) is a Compound of sliding tapered twisters (the name will be explained later). The generating process of the building volume is exemplary for the use of modelling software. The overall volume does not twist, only the volume segments outside the cylindrical core do.

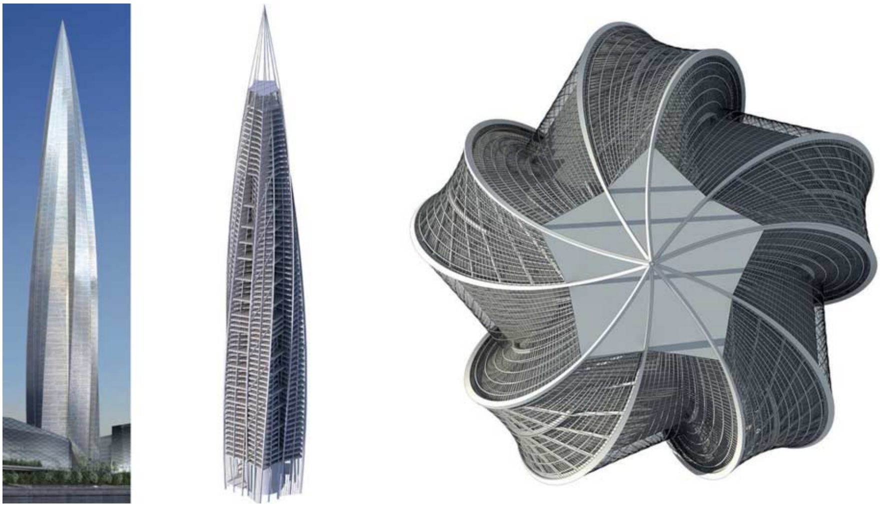


FIG. 91 Okhta Gazprom tower, planned / postponed in St. Petersburg, Russia (by RMJM); superstructure sideview; topview

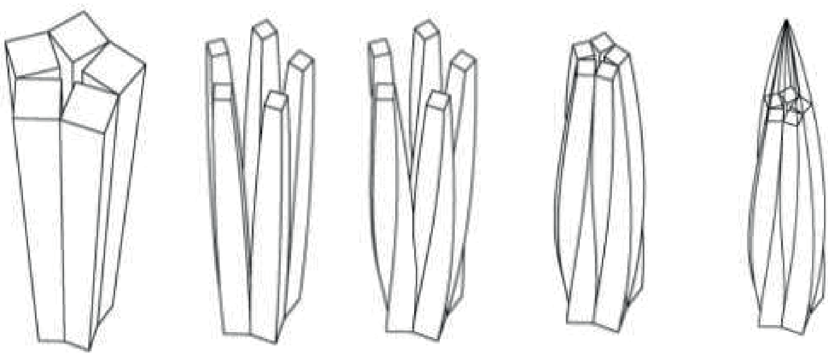


FIG. 92 Transforming sequence: scale, taper, twist, shea, merge

The volume can be generated in various ways. For example, by positioning 5 cubes on the ground floor as a five-pointed star (Figure 92). Then scaling the cubes upwards, tapering and twisting each volume around its individual central vertical axis. Next each axis is bent sideways while keeping the floors horizontal ('shearing') to make the volume's tops touch.

The model can also be scripted. Then for example the squares are drawn as ground floor plan. Similar curved trajectories for the floorplans to follow are described, or constructed on the screen. The floorplans subsequently are scripted to get smaller and rotate while moving upward along the trajectories. The top was added later in the above sequence, to outline the geometry of the first drawings more clearly. It should have been shown from the beginning, as integral part with the lower volumes. Most articulated high-rises are variations of primitive shapes. The scheme (Figure 93, 94) is based on the transforming of such shapes. Primitive shapes and transforming commands in the scheme are limited to those that are most used, to obtain a concise overview.

The in the scheme mentioned software tools are concisely described in chapter 08.08, and illustrated with architectural examples in chapter 08.09.

The Main Categories have 2 groups of volumes: Primitives and Generated Primitives.
The Primitives only have limited variations in shape, because of the geometry of their origins. The Generated Primitives, like Extruder, Revolver, Merger, Skinner, add variation to the primitive shapes. They were generated by applying deforming commands with related names. A Sphere, Cylinder and Cone can be made by rotating a generating line around an axis. They are so often used that they are listed as separate primitives. As the standard is to scale the primitive Cube into the right proportions before further transforming, the name box is used for this allready scaled shape. Less common primitives, like truncated cones, are left out. Such a primitive is classified by adding an adjective to the Sub-Category name, like Bent truncated cone.

Transformers, are the commands (shear, bend, scale, etc.) that can be applied to transform the shapes in the Main Categories. Building volumes are named according to their shape in the Main categories, with the transforming command as adjective, for example a Scaled twister. When after transforming, a primitive maintains its shape characteristics, then it is classified under that primitive's name. If not, then it is stored in the Sub-Category with the transformer adjective.

Buildings sharing a specific feature are grouped in the Special Categories. Repeaters for example, have identical façades, of Turners at least 1 floor can rotate.

08.05 THE CAD-TOOL 2.0 MORPHOLOGY SCHEME OF NON-ORTHOGONAL HIGH-RISES

MAIN CATEGORIES:

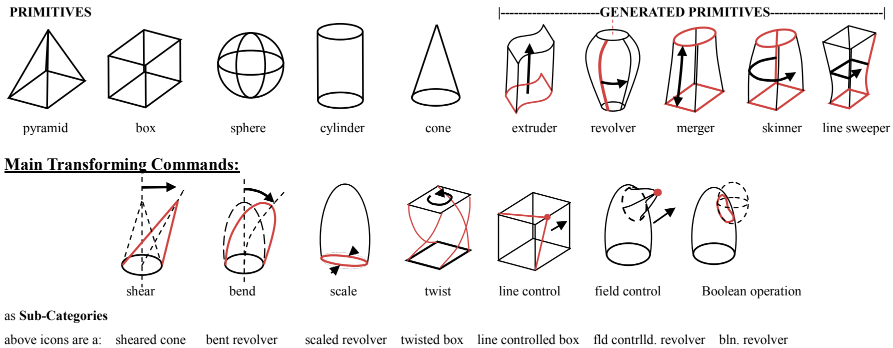


FIG. 93 Main categories

EXAMPLES OF SUB-CATEGORIES AND SPECIAL CATEGORIES:

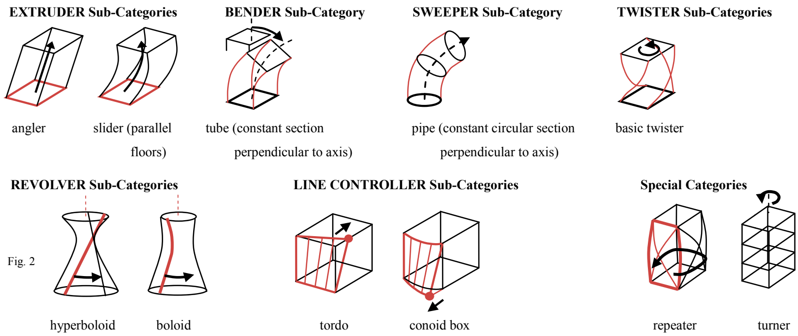


FIG. 94 Sub-categories and special categories

ELABORATION ON THE SCHEME

Transformers can also be seen as groups of volumes that a specific command was applied upon. For example, the group Twisters contains the twisted boxes, twisted mergers, etc. Some volume types are relatively easy to materialise and therefore grouped in sub-categories. Thus sheared, scaled or bent volumes are classified as Extruders when they feature repetition of floors. When for example, a cylinder is scaled sideways, its sections transform into ellipses. The scaling changes the cylinders' characteristics and it no longer is classified as the primitive Cylinder but becomes an Extruder. Anglers and Sliders are Extruder sub-categories. Anglers have an inclined straight axis along which the floors are repeated. This axis in a Slider is curved. The adjective Basic to a Transformer is used when it is a fundamental type of transforming, with fixed parameters. A Basic twister has identical floors repeated upward with a constant rotation around a vertical axis. Its façades repeat on all floor levels. The basic twister is the first generation of the twister. In the second generation twisters the parameters of floorplan contours, axis shape, axis inclination and/or rotation vary. Hyperboloids are classified as a Revolver Sub-Category. They have a straight generating line that revolves around a rotation axis. The lines neither lie parallel nor intersect. Tordos and Conoids are classified as Line Controller Sub-Categories. They are created by moving contours, while ensuring that one or more of the transformed surfaces is a ruled surface (built of straight lines). The use of parametric modeling software, stimulates application of non-standard elements. They approximate orthogonal flat products in price. The use of non-standard elements is visible in many non-rectangular high-rises; repetition of elements is losing importance now freely curved shapes can be materialised rationally. In consequence, twisted geometries with repetition of elements are applied not so much for economic gain as for semiotic connotation. Designers, clients and general public alike, are getting used to more complex geometries and their understanding of geometrical build-up grows. Use of transforming commands for building names, requires basic knowledge of modelling procedures. One need not be able to work with the software tools, only need mentally visualise the transforming principles: move, bend, twist, rotate, copy, mirror and know some primitive shapes, like box, cylinder, cone. However, as modelling software developes, numerous specific commands are made, and applied. Such commands are hard to discover, so the onlooker must be told about their existence. When the tools become more specific, less people will understand the geometrical build-up. Though this may limit the general application and acceptance of the morphological scheme, the use of specific commands is inherent to the generating process of the building volumes – and to the design tools architects are likely to apply. A durable database classifying articulated high-rises will ease retrieval of information. Such a scheme should be kept up-to-date, for example by links to the skyscrapercity.com and emporis.com websites. A keyword system is to enable data retrieval on specific functioning, finishing or shaping variety. Linking various ways of the volume generation in a keyword based database, optimises the shape retracing. Often it is hard to distinguish the geometrical build-up, and to retrace the transforming tools used. Storage of similar or alike shapes under different names, undermines the database and confuses. This, together with the further development of parametric software, may necessitate using a higher level of abstraction in a future scheme edition, for example by making it vector based. To be generally accepted, new descriptions probably must connect to the experiences in natural life. This will imply again the use of words like twist, scale and rotate. A new vocabulary may be developed on geometry, but when more abstract, it will take long to be understood by the general public. Projective geometry, making use of algorithms for the reconstruction of 3D objects from several images of that object, may be applicable to trace similar building geometries on a more global level.

08.06 CONCLUSION

Non-orthogonal buildings with curved façades can be morphologically organised in accordance with the computer manipulations used to draw them.

08.07 REFERENCES

REF. 08.01 Foa (2003). Phylogenesis, Ed. M. Kubo, A. Ferre and FOA Actar, Spain, ISBN 84-95951-47-9

REF. 08.02 Jencks, C. (1982). Skyscrapers-Skycities, Academy Editions, London, ISBN 85670-679-5

REF. 08.03 Vollers, K.J. (2001), Twist & Build, 010 Publishers, Rotterdam, ISBN 90-6450-410-5

REF. 08.04 Pottmann, H., Asperl, A., Hofer, M., Killian, A., Architectural Geometry, Bentley Institute Press, 2007, ISBN 978-0-934493-04-5

REF. 08.05 Aiello, C., (2008) Skyscraper for the XXI Century, eVolo Publishing, USA, ISBN 0-9816658-0-2

08.08 DESCRIPTION OF SOFTWARE COMMANDS APPLIED IN THE SCHEME

Commands, are the names for the software tools used for generating or transforming building volumes. For example Shear, Twist, Scale, Unite or Merge.The following describes in short and simplified various names and commands mentioned in the scheme.

Generated primitives are volumes, characterised by:

- Extruder, a closed line moved along a line;
- Revolver, a rotational volume, made by moving a 'generating line' around an axis;
- Merger, having a fluent surface drawn between two closed lines, like a circle or a square. The type of generated surface varies with the software and basically is freely curved;
- Skinner, having a surface drawn by moving a specifically chosen line along two closed lines;
- Line sweeper. This volume is created by moving ('sweeping') a curved line along a base contour (a 'closed line') as rail-track. The curve can be scripted to during the 'sweep' change in shape, inclination, rotation, etc.;
- Closed line sweeper. This volume is created by moving a closed line along a curve, the 'centre spine'. The closed line lies perpendicular to the curve. The closed line can be scripted to during the sweep change in shape, inclination, rotation, etc.

Main Transforming Commands are the commands by which a volume shape can be changed. For example:

- Shear. When the floors are moved sideways in parallel, the manipulation is called shearing. The building volume, floor height and floor contours when shearing stay the same. A volume that was transformed with this command, is named a Shearder;
- Bend. By connecting an axis to the building model and then curving the axis, the volume can be transformed with it. When the original floor contours stay positioned perpendicular to the axis when it gets curved, a bent volume results with varying horizontal sections. Such volume is named a Bender. When the section perpendicular to the axis stays the same, the volume is named a Tube, if it varies, it is a Bender. When a tube section is a circle, it is named a Pipe;
- Scale. A volume can be scaled in the directions of the 3 axis, or for example, in relation to a chosen point;
- Twist. By twisting, a volume is twisted, in relation to an axis connected to the building. The rotation can vary, and the axis need not lie in the centre of the volume, nor be straight;
- Line Control. By this command, a line on a surface or surface contours can be moved and be changed in shape. The directly connected surfaces transform with the manipulation of the line;
- Field Control. By this command a selected part of a volume surface can be transformed. The surfaces connected to the moved part, transform too;

– Boolean operations allow for quick sculpting, by for example adding (Unite) or deducting (Remove) parts resulting from intersections with other volumes.

08.09 SPHERE, CYLINDER, REVOLVER, SHEARDER, SCALER

SPHERE SEGMENTS, SHEARED REVOLVERS

FIG. 95 Westhafen Tower, Frankfurt, 2005 (by Schneider&Schumacher); Fairgrounds redevelopment, Milan (by Libeskind); Swiss Re, London, 2003 (by Foster&Partners); Communication tower, Valencia (by T. Cortez); Green Bird (by Future Systems); Torre Agbar, Barcelona, 2004 (by Nouvel)

Cylinder (Figure 95a), Cone and Sphere are primitive shapes. The Figure 95b is a Sphere segment. Rotational building models, Revolvers, are built by rotating a 'generating line' around a rotation axis. The generating line may be straight or may curve inwards, outwards or be complex-curved (Figures 95cd). Figure 95e Sheared revolver is optimised as to windage reduction in the prevailing wind direction. By shearing, the floors are moved sideways. Figure 95f Scaled sphere has elliptical floors. It can be drawn by stretching a sphere over the vertical and a horizontal axis or by moving an elliptical floor upwards while scaling it.

ANGLERS, SLIDERS, TAPERED SLIDERS, SLIDER ASSEMBLIES

The floorcontours of Extruders are identical and non-rotated. There are various sub-categories. Anglers have the floors piled under a fixed inclination. When piled under a varying angle, the buildings are called Sliders. Often a slider is built as a stacking of straight segments (angler segments) leaning in different directions, with these parts fluently connected by bent segments (Figures 96ab). Many high-rises taper to reduce windage at the top (Tapered sliders). Sliders can interconnect and form assemblies, to achieve a rigid structure, shorten traffic routes and provide alternative fire-escapes (Figures 96cd). Figures 96ef slider assemblies interconnect, intersect and merge. When the floors of Sliders additionally rotate, they are Sliding twisters.

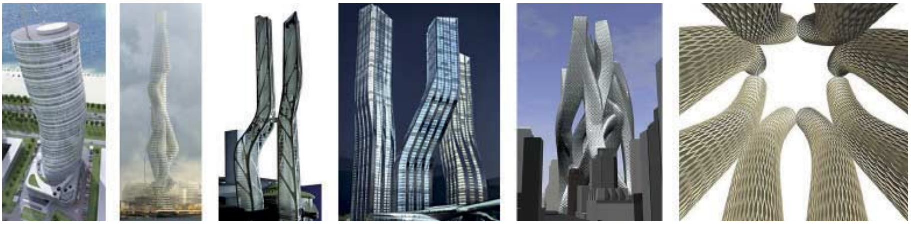


FIG. 96 Al Mutawaa tower, Dubai (by Soehne); Gazprom, Petersburg (by Herzog De Meuron); The Legs, Abu Dhabi (by Aedes); Dancing Towers, Dubai (by Hadid); Oblique World Trade Centre, New York (by NOx); World Trade Centre, New York (by FOA).

TWISTERS: BASIC AND TAPERED TWISTERS LINE CONTROLLER: TORDO

A basic twister has a constant horizontal rotation around a vertical axis and identical floors. Its façades repeat on all floor levels. The floors of Figure 97a basic twister hang rotated around a cylindrical core. The façade columns in Figure 97b incline in- and outwards, but are stepped sideways. The stepping and stiff connections to horizontal façade beams, greatly reduce torque. Figure 97c compound twister has a twisting volume intersecting an orthogonal elevator shaft. Vertical recessed columns are positioned in a circle and the façades hang from protruding floors. Figure 97d tapered twister has inward curving transoms. This is unusual, as it implies a less efficient floor/façade ratio. Tapering decreases the repetition in upward direction. This is compensated by horizontal repetition. A tordo has an orthogonal superstructure and one or more twisted façades that do not share a rotational axis. The Figure 97e tordo can be drawn by curving some contours. All mullions connect to parallel flat walls. Not so in a twister: it's helical mullions lean sideways, and it's façades share the rotation axis. The 632 m high Shanghai tower, a tapered twister, will be organized as nine cylindrical buildings stacked atop each other, enclosed by the glass façade's inner layer. Between that and the twisted outer layer, nine indoor gardens at different levels will provide public space.

FIG. 97 Turning Torso, Malmö, 2005 (by Calatrava); Infinity Tower, Dubai, -2011 (by SOM); Avaz Twist tower, Sarajevo, Bosnia-Herzegovina, 2008 (by ADS Studio); Fordham Spire, Chicago, on hold -2013 (by Calatrava); Ocean Heights One Residential tower, Dubai, -2010 (by Aedes); Shanghai Tower (by Gensler, Jun Xia).

TWISTERS: SLIDING, HELICAL, TAPERED AND MERGING TWISTERS

FIG. 98 Different highrise twisted towers: Torre Castelló, Valencia (by Calatrava); Cobra Towers, Kuwait; Twisted Trees, Bin Hai Seaport City, China (by Lee Harris Pomeroy); World Business C., Busan, S. Korea (by UNStudio); Bicentenary Towers, Mexico City (by Vasquez & Wedeles); Dubai Towers, proposed (by TVS).

BASIC TWISTERS: STEPPED TWISTERS, HYBRID TWISTERS

As yet fluently curved/twisted glass panes have not been produced on a scale for high-rise. All façades are tessalated with flat panes. Just like the underside of a set of stairs, a twisted surface can be approximated by flat surfaces. The façades of stepped twisters are composed of flat segments (Figure 99a). Torsion on the superstructure caused by inclining columns, is reduced by decreasing the protruding of wings. Often a twisted volume is simplified to a combination of cylindrical surfaces and stepped flat surfaces (Figures 99c). Hybrid twisters have façades of various geometries, that fluently connect (Figure 99bde), like cylindrical and twisted segments. Figure 99d stepped hybrid twisters feature both aspects.

FIG. 99 Different basic twisted high rise towers: Urban Totem, Mississauga, Canada (by Donner&Sorcinelli); Kuwait Trade Centre, 2009 (by NORR); Mode Gakuen Spiral tower, Nagoya, Japan, 2008 (by Nikken Sekkei); Torre Alicante and Torre Valencia, Valencia, Spain (by Calatrava); Sea Breeze tower, Dubai (by author)

MERGER, BOOLEAN, LINE CONTROLLER

Whereas Mergers are primitives, Booleans and Controllers are transformed primitives. The façade of the Figure 100a tower seems to transform from a circular base to a free curving roof contour, making the volume a Merger. But the façade can also be standardised to cylindrical segments, with flat parts inbetween. Uncertainty leads to classifying it a Free shape.

FIG. 100 Different examples of 'merger'type high rise buildings: Iris Crystal, Dubai, planned (by Aedes); Opus, Dubai, -2010 (by Hadid); Gazprom, Petersburg (by Herzog & de Meuron)

Booleans are volumes sculpted by deducting or adding volume segments that are described by intersections with other volumes. Their surfaces typically meet along clearly visible lines. Figure 100b Free shape has a canyon-like cut-out. It may be a Line controller, shaped by making orthogonal cut-outs from a box volume, and then transforming the surfaces by curving some contourlines. Compound volume Figure 100c is a Compound of boolean extruders, consisting of two overlapping volumes. The volumes were extruded from the base contours upward, and had with boolean operations parts removed. Fig. 100d is a Boolean on which intersecting curves were drawn. These were used to make contourlines around surface fields, that subsequently were filled with glass and hole patterns.

FREE SHAPE, SWEEPER

Figure 101a Free shape probably was drawn with few manipulations, but it is not obvious which. It can be a line sweeper – a volume created by moving a curve along a base contour as rail-track. Or be a scaled extruder – made by first extruding a base contour upwards, then scaling it and adding a twist. Especially when the rotational axis is curved or the scaling varies and is excentric, determining the transforming process is hard. Additional transformations will complicate retracing the shape build-up even more, especially for those not accustomed to drawing. Then the client, architect or contractor may have to supply the information for the database, by naming the commands used to generate the building volume, preferably in order of application. Figure 101b volume, generated by applying various tools, is a Free shape. The Figure 101c volumes twist and taper. Especially when tops are cut of under an angle, and no patterns of for example repeating lines can be distinguished, then determining the geometry is hard. They are classified as free shapes, as the façades are a mix of flat, singlecurved and (hyperparaboloid) twisted segments. Both Figure 101d free shapers were designed by first optimising three stacked different volumes to accomodate apartments, hotels and offices respectively, and next adapting the volume contours to visually fluently interconnect. Subjective finetuning, will make a shape only globally fit the morphology system.

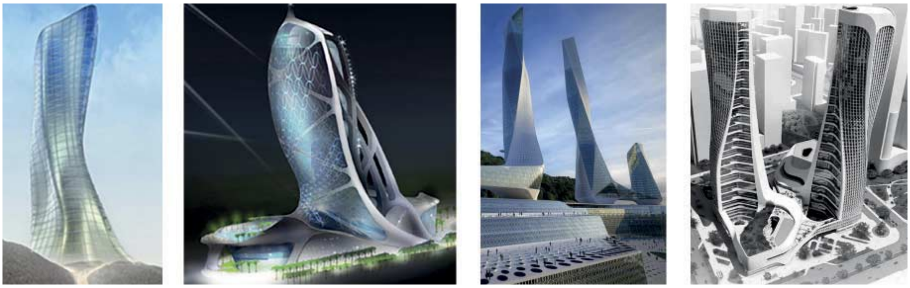


FIG. 101 Desert tower, Peru (by Ferri); Hydropolis Dubai, proposed (by Hauser); PGCC, Penang, Malaysia, proposed (by Asymtote); Raffles City, Hangzhou, China, -1012 (by UNStudio)

COMPOUND VOLUMES: CONNECTORS, BLENDERS

A Compound volume is a volume built by combining two or more complex shaped volumes. It differs from a Boolean, which is made by transforming a primitive shape, by for example adding or deducting (parts of) a volume. Figure 102a shows a cluster of compound volumes, each composed of interconnected or overlapping segments. The recessed façade segments may have been made by intersecting outer volumes with an inner one, or by merging surfaces between lines drawn on the volumes. Figure 102b is probably generated by projecting curves onto a volume and demarcating fields with them, which subsequently were, for example, pulled outward with 'control lines' acting like magnets and were divided into horizontal bands. As the originating primitive shape is uncertain, this volume is classified as a Free shape. Figure 102c is a compound volume with lower segments sheared sideways or at least the façades there blended to the surrounding earth surface. Figure 102d is a compound of tapered sliding twisters.

FIG. 102 Farrer Road towers, Singapore, proposed (by Zaha Hadid); Urban Oasis, Singapore (by UNStudio); M. Schumacher tower, proposed. Dubai (by L-A-V-A); SOCAR tower, Baku, Azerbaijan,

SPECIAL CATEGORY: PUNCTUATED TOWERS

Figure 103abd are Booleans. Figure 102a is a Boolean sphere with holes cut out where it overlaps with other spheres. Figure 103b is a blended Boolean extruder. The overall volume was shaped by deducting parts from a volume that was made by extruding a base contour upwards. Subsequently the contours were blended: rounded of with a fixed curve. Figure 103c is a Free shape, as many transforming tools were applied to shape it. Figure 103d is a Boolean box with spherical holes.

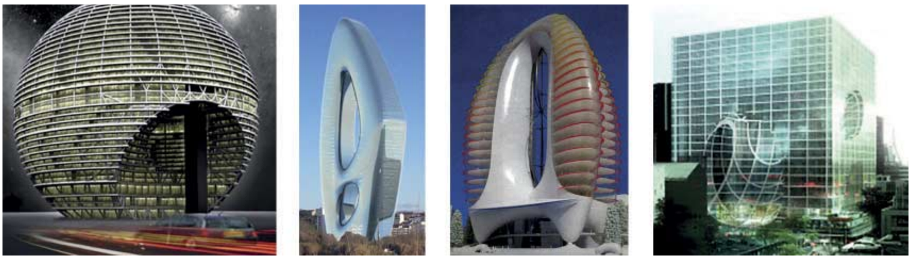


FIG. 103 RAK Convention and Exhibition Centre, Ras al Khaimah, UAE, proposed (by OMA); Vertical Learning Centre, Portugal (by B. Silva); Bionic Tower (by Future Systems) ; Coolsingel Tower, Rotterdam, proposed (by OMA).

SLICERS

A Slicer appears to have a curving façade, this impression being created by balconies, louvers or other protruding elements. In Figure 104a the curving virtual outer surface is indicated by balcony contours meandering around an orthogonal glazed volume. The balconies of Figure 104b have recessed façades tessalated with flat segments.

The smooth image on Figure 104d is achieved by the large number of thin sun-louvers. The Figure 104abcd volumes are molded by various transformations. As their geometry is not obvious, they are Sliced free shapes. Verticality of balustrades is less obvious on the high-rise Figure 104c than on the low-rise Figure 104e Sliced twister, where the overall look is not smoothly curved but stepped.

FIG. 104 Aqua tower, Chicago, -2009 (by Studio Gang); Tower, Oslo, Norway (by MAD); Absolute World 1, Mississauga, Canada, -2010. (by MAD); Slinky Twins, Paris (by PCA); Nordhavnen Residences, Copenhagen (by 3XN)

TURNERS

In 1924 the Russian constructivist Konstantin Melnikov designed the Pravda Leningradskaja office building. The floors were to hinge around a steel core, each rotating approx. 60°. In 1927, Buckminster Fuller proposed his Dymaxion House; the bungalow could follow the sun, pivoting around a mast. Later the principle was applied in various houses, like the 4-storey Heliotrop designed by Rolf Disch in 1994.

FIG. 105 Rotating Residences, Dubai, (Faisal Ali Moosa); Time Residences tower, Dubai, (Howells/Palmer&Turner); Da Vinci tower, Dubai / Moscow, (Fisher); Dubai Renaissance, (OMA).

Recently architects have proposed various Turners: towers that can rotate as a whole, or in part(s). The top 5 of the 15 floors of the Rotating Residences (Figure 105a) are to rotate individually. The Time Residences tower (Figure 105b) is to rotate as a whole. The Da Vinci

(Figures 105c) floors are to individually rotate, allowing one appartment owner on each floor optimal sun-light and outward view. It is the first designed to have floors programmed into a ballet-like scenario. The Dubai Renaissance (Figure 105d) is a 300m high slab with a visual play on a transformed grid. The preliminary design idea to rest the volume on a circular float so it could rotate and play a moving role on an urban scale, was abandoned.

BIO-CLIMATIC TOWERS, WIND ENERGIZERS

The boolean volume in Figure 106a has cylindrical façade segments. Bio-climatic performance is elaborated in all building geometries. Figures 106bd are Revolvers, Figure 106c is a twister. Whereas bio-climatic buildings usually function with low wind velocities and are open to the surrounding climate, Wind-energizers tunnel an accelerated windflow to activate generators. They in contrast usually have a closed climate system and smooth façades to ease windflow. Façades around wind-apertures for optimal windflow have slight curvatures and rounded building corners. Often these are boloidal, to provide element repetition. Figure 106e is a Boolean extruder. High-rise wind-energizers can have wind generators of various kinds and on several levels: Lighthouse, Dubai (1 tower), WTC, Bahrain (2 towers), Atrium City Towers, Dubai (3 towers). Volume configurations were studied in for example, Land's I.I.T. workshops.

FIG. 106 EDDIT tower, Singapore, proposed (by Yeang); Commune towers 2026, Seoul (by Yeang); Sustainable tower, Dubai (by AlBaloushi); Innovatoren, Venlo NL (by McDonough + Arcadis); WTC, Manama, Bahrain, 2008 (by Atkins)

CLUSTERS

Usually the base and top of towers line up with important urban elements like a road or canal. The Twister twins in Figure 107a twist approx. 90˚. Sharing directions of top and/or base, unifies towers. Many iconic buildings stand alone and mostly refer in direction to themselves, i.e. their top takes up the directions of their own base, as indeed they are the most important urban element. A building rotation of 90˚ can bestow a crystalline beauty like that of a cut jewel. Abbreviating from 90˚, introduces natural associations and draws the attention away from the building. A singular iconic tower or a line-up of towers, pinpoints a project. When similarly transformed buildings encompass a setting, then an environment is created. Such towers need not be identical. With a limited number of parameters in the modeling, many variations can be made, like a Slider cluster (Figure 107b) and a Line Controller cluster (Figure 107c). Embedded formal harmony between buildings stems from sharing 'genes'.

FIG. 107 Dubai Towers, Istanbul, proposed (by Inhouse Design); Caribbean, Keppel Bay, Singapore (by Libeskind); Dostyk Business Centre, Almaty, Kazakhstan (by NBBJ).

FAÇADE PATTERNS

Avant-garde architects use modeling software to visualise new façade styling, geometries, textures and functioning. 3D printing is becoming economically feasible for production of large series of small building components. In time it will allow grading materials (varying the materials' consistency and density), ease assemblage, add new functionalities (such as the capability to ventilate), etc.

In morphogenetic façade design, patterns are generated by scripting relations between components to define their sizes and positioning. Building skins become 'populated' with windows or structural elements. Figure 108a Boolean extruder is an extruded volume with façades perforated by intersecting with cylinders. The hexagonal façade openings of Figure 108b vary also in size, but are flat. The Figure 108c box features a cubic lattice undergoing cycles of disintegration, migrating from order to chaos and back again. The façades of Figure 108d has folds in the glass (!) and other panels. The façades of compound volume Figure 108e are compilations of bulging elements of varying size.

The gap between patterning and structural optimisation narrows, Figure 109a.
The SmartGeometry Group specialises in applying associative geometry with Generative Components software. One of their workshop studies was on helical surfaces populated with components which correspond to local stress, Figure 109b. Scripting procedures are applied to visualise and develop integrated functions, Figure 109c. Unexpected images can thus be generated, but they often require subjective visual finetuning. The response of future high-rises to the historical and social context, urban fabric, new materialisation and added functions, is visualised in, for example, design entries for the Evolo Skyscraper Competitions. [AIEL, 2008] Their shaping as yet has not yet been classified. They can be listed in the Free shapers, or in special categories, like Structural façade patterns, Urban models.

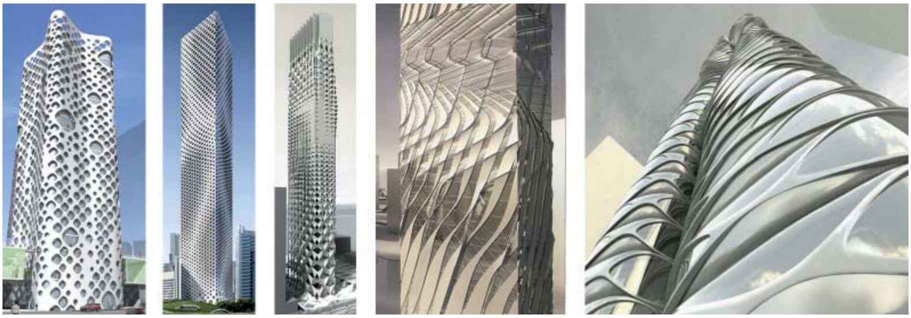


FIG. 108 : O-14 tower, Dubai, -2009 (Reiser & Uemoto); Sino-Steel tower, Tianjin, China, -2012 (MAD); Tower project (Ali Rahim & Yeung); Residential tower, Dubai and Commercial Office Tower, Dubai (Rahim).

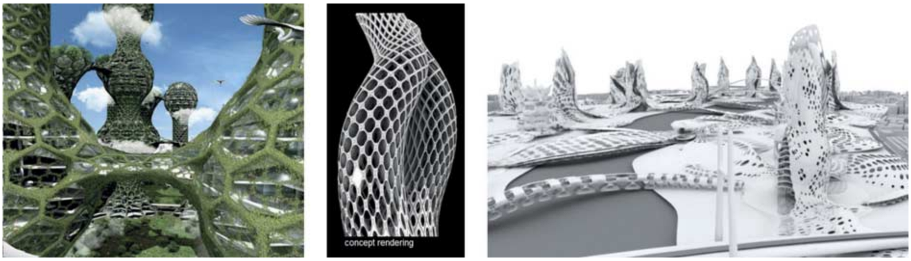


FIG. 109 Free shapers

09 UPGRADING BUILDING APPEARANCES BY IMPROVED PANE REFLECTIONS

Karel Vollers

09.01 FREE-D GEOMETRY

The glass industry only partly meets the architects wishes as to regularity of reflections. In their plans the spectacular reflections on curved façades are elegantly curved, but when realised, they often are optically distorted. To achieve a dramatic visual effect, transforming of reflected images must be clear and smooth. Some optical effects are illustrated in this article. The causes of distortions are divided in two groups: those surface irregularities inherent to the pane production and built-up and those that follow from the pane mounting to a building. The main causes of distortions are schematised and elaborated on. The accurate mounting of panes is exemplified with the newly developed Twist-framing system.

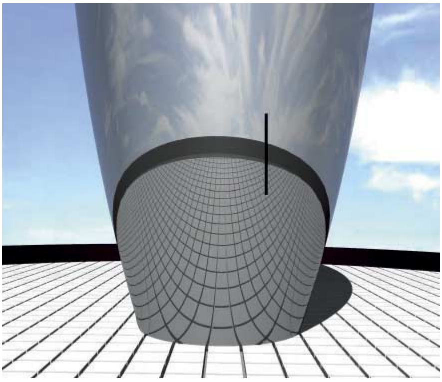


FIG. 110 Ellipsoid volume: intersection line curves forward: upward curving horizon reflection.

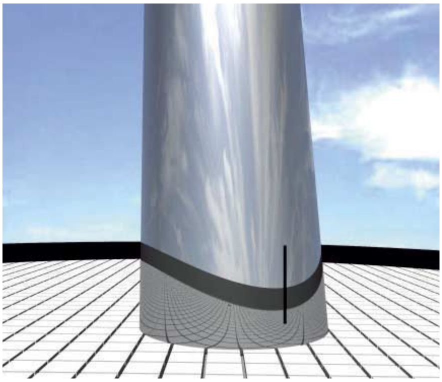


FIG. 111 Sideways inclining cone: intersection curving backward: downward curving horizon reflection.

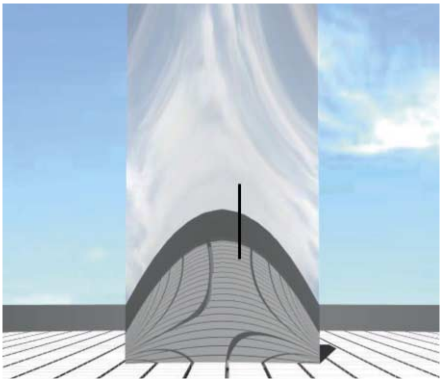


FIG. 112 On this twisted surface with vertical sides, the centre straight line inclines forward. With curvatures in opposing direction, the reflection narrows and widens.

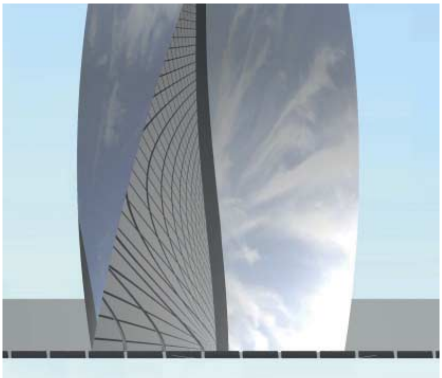


FIG. 113 Perspective of a twisted tower designed by author, with both forward and backward inclining façades.

When a façade curves, a rule of thumb quickly gives insight into what reflection transforming results. The formulae is based on a imaginary vertical flat surface through the viewers eye intersecting the curving façade. The intersection line will be curved. If this curve inclines forward, the horizon reflection will bend down on both sides of the intersecting curve, or in other words, there the reflected horizon bulges upward. If the intersecting line with the façade curves backward, then the reflected horizon bulges downward.

If a horizontal intersection line (of a horizontal surface through the viewer's eye and the building) curves forward in the middle, then the segment of the horizon that is reflected, will widen and the objects on the reflected horizon will be squeezed together. If it curves backward, the reflected horizon segment gets smaller, and the objects on it are widened.

When the reflecting angle of the viewer to the building changes quick, the image quickly widens or narrows too – reflected neighbouring towers then are squeezed together or are widened. On an anti-clastic curvature (= with 2 opposing curvatures), the image in 1 direction is squeezed, and in the other direction is enlarged.

A grid on ground level, and pronounced geometrical shapes in the surroundings, ease understanding how the reflected and the original image are related. Unwavering long transformations ease finding the origins of the reflected image. Hereto panels must be smoothly transformed.

BLURRING OF REFLECTED IMAGES

When images are distorted by irregular transforming, they get 'blurred'. Improved surface smoothness leading to less blurring, is not always wanted. Most firms don't want a perfect reflection of a competing neigbour, on their facade. Neither will they want to emphasize a chaotic urban setting by multiplying such scenes on their façade. Distortions often will be acceptable, or even be appreciated. A neighbour's reflection can by blurring and fragmenting be turned into an elegant ornamental façade pattern. Transformed reflections caused by curving of a façade can add value. They challenge the mind by their geometrical play, and surprise. They demonstrate control of technology, visualise economic power and thus add positively to the owner's identity. Often distorting is hardly recognisable, or negligible. Then it is a waste to spend money on improving the pane's regularity. The pane positioning is an important aspect. High up in a façade, highly reflective glass can be used, as distortions will hardly be noticeable. Especially as cloud reflections hide blurring of the panes anyway. In contrast on lower levels it often is better to apply 'see through' anti-reflective coatings and clear glass, to avoid reflections, or unwanted blurring.

The general trend is to achieve more smoothness. Smoothness adds value, which may well be exemplified by the fact that hardly anyone will still buy a car with distorting windows when a perfect reflection is obtainable for the same costs. As the market demands best quality, all small improvements are selling arguments, both for automotive and for architectural glass. But it is of limited effect to spend a lot on improving a minor distorting factor. Costs of correcting a singular distorting effect are related to the overall distortion by all other factors.

MEASURING GLASS DISTORTIONS

Distortions in freely curved panels can be quantified and visually judged in similar ways as those of glass of simpler geometry, like cylindrical and conical glass. Global curved glass and other surfaces of rotation can be heat treated. The adjusting of the quenching system is a manual operation, and therefore generally only affordable for series of panes. No installation is as yet available to quench freely curved glass. Such panes can as yet only be chemically strengthened.

There is no industry specification for acceptable curvature distortion level, so, this is an area where an acceptable maximum must be proposed that can be met during the project. This however is complex to measure on a freely curving pane. An appearance defect is defined by a fast variation in the local slope across a short distance, depending on the altitude and the wavelength. The appearance defect can thus be characterised by the spatial derivative of its slope, or the second derivative of its altitude, namely the curvature. [AND] The peak to valley distances can also be described in millidiopters like in the GANA test method. [GANA] The peak to valley distance must be seen related to the wavelength, as it impacts local curvatures. These methods were designed to measure rolling waving by tempering; their appropriateness for measuring irregularities in freely curving panes is limited. New optometric methods will be developed to measure geometrical irregularities. Panes can be inspected by looking at the reflection of a zebra board. This method does not quantify distorting, but it gives a qualitative way to determine irregular overall bending and curvature defects for example along pane borders.

For overall bow and warp, there in ASTM C-1048 is a table for maximums allowable depending on glass thickness and size. [ASTM]

MINIMISING GLASS SURFACE IRREGULARITIES

Pane surface irregularities are caused by:

1. The pillow effect on an insulating pane, caused by different gas pressure in cavity and outer sides. The varying pressure usually is caused by temporal changes in atmospheric conditions:
   - long term: periods of high/low air pressure (like depressions) or average seasonal temperatures;
   - short term: wind;
   - permanent differences in atmospheric pressure:
   - the height of building site relative to factory;
   - the various heights at which panels are positioned on the (ultra-) high-rise building. Also temperature differences can be the cause, by solar heating of panes as well as by varying temperatures during day, in and outside the building. Occasionally panel transport across mountain ridges causes permanent distortions.
2. Production tolerances deriving from:

- heating and cooling process:
- varying glass temperatures due to glass qualities (reflective layers, glass thickness);
- atmospheric conditions (humidity, etc);
- incomplete sagging onto mould surface (full-surface, for example milled) or too much sagging (between the interspaced bars of a mould surface);
- cutting to measure before or after sagging, i.e. cutting of distortions along panel surface edges;
- Production tolerances following from tempering are not applicable as this technology isn't available now for freely doublecurved glass.

3 Tolerances during panel assemblage in factory. Incorrect geometry of assemblage table during assemblage (and sealing) into insulated and/or laminated panes

4 Tolerances connected to the framing:
- inaccurate frame curvature This can be avoided by not using a framing;
- inaccurate connecting tolerances of framing or point fixtures to building superstructure;
- varying pane bending by tolerances in fixing pressures to the frames.

5 Varying gravitational bending of the pane because of the double curved façade's inclination.

This effect as yet is disregarded, because the varying degree of bending and the relatively small transforming, now make it too expensive to correct.

The main causes of surfaces deflecting from the intended shape are pillow working and production tolerances. Only the pillowing effect will now be discussed. Visible pillowing on the exterior of the façade can be avoided or minimised by:

- using only a single pane on the exterior, and positioning separately an insulating pane on the inner side of the façade eliminating expansion of gas in the cavity, by assemblage into vacuum glass;
- eliminating change of pressure in cavity by ventilating the cavity. This implies applying dehydrating air-channel spacers or a dehydrating container, after 10 year change container;
- making the outer panel thicker than the inner-side pane. For example by increasing the outer pane thickness, or by laminating it. Often with an inclination >10°, laminating is obligatory anyway.

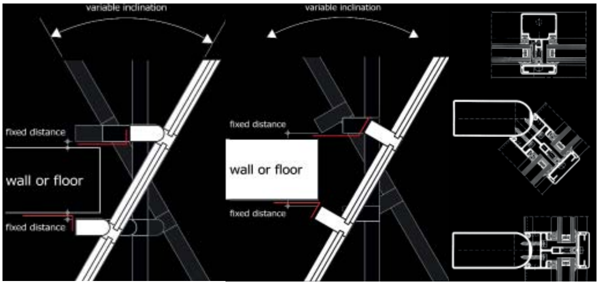


FIG. 114 Varying connecting angle of façade to superstructure (e.g. columns, walls, floors)

- varying meeting angle of glass to transom and to mullion;
- connections to walls + floors vary in height + angle;
- complex production + assemblage;
- extensive measuring;
- 3b. The standardised Twist-system connection:
- right angled or parallel connection to floor or wall: easy assemblage and measuring;
- rigid backing profile of simple section (straight or single curved): easy production and bending;
- torsion-weak glazing profile: parallel connection to panes;
- 3c. The Twist-profile is split in two parts that connect along a cylindrical surface;
- 3d. 2 x 2 m freely curved showroom model with opening window.

Freely double curved façades meet a floor, wall or ceiling under a varying angle.
The Twist-profile system is designed to standardise the connections of profiles to both floors and to panes. [VOL]

The system is based on splitting a standard profile in two, resulting in a backing and a glazing profile. The backing profile is straight or single curved, and positioned in a standardised way parallel or perpendicular to the building's superstructure. The glazing profile connects parallel to the panel. The two profiles meet along a cylindrical surface. Whereas the backing profile provides structural strength, the hereto attached glazing profile has little resistance to torsion and bending. Bending the backing profiles of simple section in one direction is relatively easy, as compared to bending and twisting them, and the glazing profiles are manually bent – on façades of big curvature.

The showroom model as illustrated here, has a straight bottom transom, while top and standing profiles curve with a radius of 4 m. The pictured Alcoa AA100Q–Twist profile series is integrated in an internationally distributed profile range. [ALC] It optionally has opening windows. A variety of outer finishing can be chosen from or varied on, for example application as a structural glazing. By operating one handle, the window locks at five points to the surrounding frame. Connecting rods between handle and locking points continue through the bent and twisted window profiles, and around angled corners.

REFERENCES

REF. 09.01 [AND] Anderson, P., Quality control in Flat Glass Production, Glass Processing Days 2005

REF. 09.02 [GANA] GANA TD 04-03-26, Standard Test Method for In-Plant Measurements of Roll Wave in Heat –Treated Architectural Glass. Glass Association of North America, Topeca, KS

REF. 09.03 [ASTM] ASTM Standard C-1048-04, Standard Specification for Heat-Treated Flat Glass – Kind HS, Kind FT Coated and Uncoated Glass, American Society for Testing Materials, West Conshohocken, PA

REF. 09.04 [VOL] Vollers, K.J. and Van den Engel, G., Framing Systems for Façades of Non-Standard Geometry, Glass Processing Days 2005

REF. 09.05 [ALC] for more information: wimj.h.bergvanden@alcoa.com

ACKNOWLEDGEMENTS

Alcoa Architectural Systems (NL), Glaverned (NL), Van Campen Aluminium in Lelystad (NL), Glasbuigerij Bruining in Dordrecht (NL), Komplot Mechanics in Delft (NL), TO&I of Delft University of Technology (NL), Hellevoort Visuals (NL)

10 FINDING FREE FORM DESIGN

Walter Lockefeer

The use of computers in architectural design has changed over the years. Currently the application of computers differs amongst architects, especially in the design of Free Form Design buildings. This paper concentrates on the influence of computers on the Free Form Design process and on the design as a resulting product. In particular the evolution of the impact that computers have to develop from highly qualified draughtsmen to design decision makers. This study offers a theory of methods which, why, when, where and how computers (programs) are involved in Free Form architectural designing and the specific consequences of different kinds of application. By use of both literature studies and active reproduction of design steps by computer programs it was concluded that there are four types of computer application levels to be distinguished: Tradi-digital, Semi-digital, Formal-digital and True digital.

10.01 INTRODUCTION

Pre-historic or early Free Form Designs (FFD) were designed and built in the first 6 decades of the 20th century without the help of computers (Gaudi, Saarinen, Steiner, Otto, etc); for the simple reason that computers were either not invented or equipped for that task yet.

In the early 1970s, a need for rationality in the design process was beginning to gain ground, primarily due to the introduction and the rise of the computer as a logical device. Rather than competing with or replacing designers and architects the approach in the 1980s was predicated on the belief that the computer should assist in the design process. It was introduced as an aid for the goals and aspirations of the designer. In the 1990s the computers were able to carry out simulated environments and complex drawings. The original goal of the introduction and development of the computer in the building process was to free the architect from repetitive or time consuming work. This process is known as 'Computerization'. Now the possibility has arisen to empower the architect with new means to explore beyond the traditional framework of traditional design: 'Computation'.

Computerization is the act of entering, processing, or storing information in a computer system; it refers to the process of furnishing data within a computer or a computer system. Computerization is about automation, mechanization, digitization, and conversion of data. Generally, it involves the digitization of entities or processes that are preconceived, predetermined, and well defined.

Computation is about the exploration, mainly by means of specialist computer programs that are uncommon in the building industry, of indeterminate, vague, unclear, and often ill defined processes. This includes phenomena ranging from human thinking to calculations with a more narrow meaning. In practice, digital computation is often used to simulate natural processes (for example, Evolutionary computation), including those that are more naturally described by analog models of computation (for example, Artificial neural network). Because of its exploratory nature, computation aims at emulating or extending the human intellect. It is about rationalization, reasoning, logic, deduction, induction, extrapolation and estimation (Terzidis, 2003). This type of modeling can only be done by specialists in computation.

Computerization assisted in quality and perfection, but Computation changed the freedom in architectural design in a revolutionary way. Architectural form used to appear as the ultimate result of a process that was dominated by creativity and intuition – more or less a black box – instead of being the result of an analytic and generative research. Its beauty was the beauty of the end of the point of equilibrium. (Picon, 2003) A computer generated architectural form on the other hand, can no longer pretend to achieve this status because it is the result of a temporary or permanent stop in the endless process of geometric transformation. This type of process is called by Greg Lynn "Animation" (Lynn, 1998). Architecture and especially Free Form Design became more than the classical Vitruvius' combination of 'Solidity, Utility and Beauty (Firmitas, Utilitas, Venustas: Vitruvius); architecture, like science, is about the way we 'make' worlds, worlds populated with subjects and objects the definition of which are always historically determined (Goodman, 1978).

Most sciences have their own specific scientific methods, which are supported by methodology (i.e., rationale that supports the method's validity). Generally architecture is not based on a specific scientific methodology. The kinds of problems that architects tackle are regarded as "ill-defined' or 'ill-structured, in contrast to well structured or well defined problems with clear goals, rules or proceedings as methodology. (Cross, 2008).

Architectural problems usually are intertwining of many different aspects. So at the start of a design process, the architect is usually faced with a very poorly defined problem. As Jones (1992) has suggested: "it is therefore appropriate to think of an architect as an explorer, searching for the undiscovered 'treasure' of a satisfactory solution. The ability to design depends partly on being able to visualize something internally, in the 'mind's eye', but perhaps it depends even more on being able to make external visualization; drawings are a key feature of the design process." In practise this means that during the design process the architect experiences that the clearer the direction of a solution becomes, the clearer the problem becomes or the sharper the borders of the original problem are defined.

In the traditional architectural design process three levels of design-drawings are distinguished as functional:

- preliminary design drawings;
- definitive or final design drawings;
- building preparation or working and shop drawings.

This classification runs parallel with the phases in the building preparation process. It's obvious that the earlier a computer program is chosen and imbedded in the design process the more influence it might have. Besides the specific program chosen, four aspects of implementation will have influence on the design and engineering process, each in their specific way. The influences of these aspects are related to the reason why, the time when, the place where and the way how the computer program is imbedded in the design process. For example the use of scripting at the beginning of a design process has a totally different influence on the design process compared to incorporating computation at the end of the design process. In the latter situation the computer is merely used as a tool for solving form questions. This is in contrast with the cases where the computer creates the actual design of the building.

It seems that the specific mix of the 'which', the 'why', the 'when', the 'where', and the 'how' is leading in the influence that a computer program has on the design process.

Theories of science processes are believed to be contrasting with theories of design processes (Roozenburg et al. 1998). Specifically in architecture, theories of design processes are sets of general, abstract ideas through which we understand and interpret the material phenomena the world offers to our experiences. They deal with how the world is, not how it should be. Because designing/architecture is creative it requires a theory of possibility in the sense that they exist in art and because architecture is also predictive, it needs analytic theories (Hillier, B, Space is the machine, 2007)

This study presents a theory of methods which, why, when, where and how computers (programs) are involved in the development of Free Form Designs and the specific consequences of the different kinds of involving. The fact that Free Form Design architecture is highly related to both computerization and computation, in contrast with the current architectural practice, makes research on Free Form Design Architecture most suited to be analyzed and cover the whole range of used methods. It gives an interpretation of the current state-of-the-art and expectations for the future. The benefit of this knowledge is that FFD can be better understood, judged and, even more important, better conceptualized.

METHODS/METHODOLOGY

The research was conducted in three steps. Firstly a literature study was preformed about design and research methodologies that might lead to insight in a general methodology for the application of computer tools in the design process of FFD. Furthermore a study was performed into general computer use in architectural design.

Because the first research step showed that the best way to study the actual design process is by redoing certain actions (reconstructing the computer application) the second part of the research aimed at gathering as much information about the design processes of FFD buildings. In total more than 40 FFD buildings were studied. With this information it became possible to reconstruct the building designs in computer models. This action was performed for over 40 FFD buildings .

Table 2.1. Studied FFD Buildings

– Zaha Hadid	Victoria House, London	2003	www.zaha-hadid.com
	Soho Forum, Beijing	2004	www.zaha-hadid.com
	Islamitic Art Centre, Paris	2005	www.zaha-hadid.com
	Museum Saadiyat	2005	www.zaha-hadid.com
	Dubai Design for Opus, Dubai	2006	www.zaha-hadid.com
	Nuragic, Cagliari	2007	www.zaha-hadid.com
	Contemporary Art Container	2007	www.zaha-hadid.com
	Civil Court, Madrid	2008	www.zaha-hadid.com
– J. Majer	Metropol Parasol, Valencia	2006	www.jmayerh.de
– M. Fuksas	Milan trade	2004	www.fuksas.it
	Euromed Marseille	2006	www.fuksas.it
– Morphosis	Guggenheim, Guadelagara	2004	www.morphosis.com
	Phare tower, Paris	2010	www.morphosis.com
– Frank Gehry	EMP building, Seattle	1999	www.gehrypartners.com
	Guggenheim, Bilbao	1997	www.gehrypartners.com
	Museum, Saadiyat	2006	www.gehrypartners.com
– Coop Himmelb(l)au	Opera house Ganzhou	2003	www.coop-himmelblau.de
	Stadion, Shenyang	2005	www.coop-himmelblau.de
	JVC, Guadelagara	2008	www.coop-himmelblau.de
	House, Arlborg	2009	www.coop-himmelblau.de
– UN STUDIO	Station, Arnhem	1999	www.unstudio.com
	Te Papa museum, Auckland	2005	www.unstudio.com

	Mercedes Benz, Stuttgart	2006	www.unstudio.com
– Reiser Umemoto	Alishan, Taiwan	2003	www.reiser-umemoto.com
	A-EON, Dubai	2006	www.reiser-umemoto.com
	Dubai	2007	www.reiser-umemoto.com
– Eisenman	City of Culture	1999-	www.eisenmanarchitects.com
	Domplatz, Hamburg	2005	www.eisenmanarchitects.com
– Eric Owen Moss	NH Theather, St Petersburg	2003	www.ericowenmoss.com
	Republic square, Almaty	2003	www.ericowenmoss.com
	Peak, Gangzhou	2004	www.ericowenmoss.com
	Future city, LA	2006	www.ericowenmoss.com
– Kas Oosterhuis	Hyperbody Pavilion, Delft	2006	www.oosterhuis.nl
	The Cockpit, Utrecht	2006	www.oosterhuis.nl
– VVKH	The Wall, Utrecht	2008	www.vvkh.nl
– Asymptote	Hydra Pier, Haarlemmermeer	2004	www.asymptote.com
– AA School	Various Projects	2006-2008	www.aaschool.ac.uk

This third step provided insight in the modelling actions and computer functions that were used to reach the actual form. It showed the complexity of the design in relation to the computer facilities and the role of the computer in creating the design. With this information it became possible to distinguish between projects based on the necessity of computer use and the actual use of the computer, but also on the level of complexity in this computer use.

This last step required thorough knowledge of the main computer programs available, therefore the selection of the buildings studied was limited by the fact that it ought to be possible to draw them in Rhino, Maya or 3D Studio Max. As these are the main computer programs used in architectural offices and they provide for unlimited form freedom in drawing this was not a problem.

A lot of information was also drawn from the complexity of the form of the design. It became possible to bring order in the list of buildings based on their form complexity. It was established that the complexity of the form was an indication for the way the computer was used and whether this could be classified as computation or computerization. All three steps together made it possible to come to a classification of design processes in FFD architecture based on the role of the computer.

10.02 RESULTS

Based on the information gathered it was possible to come to a four way division in computer approaches for designing FFDs:

- Tradi-digital;
- Semi-digital;
- Formal-digital;
- True-digital.

TRADI-DIGITAL FFD

In the Tradi-digital FFD way the complete conceptual formalisation and realisation of a design take place outside and without the computer. The only function the computer has is that of a draughtsman, taking over a hand sketched conceptual design; similar to the traditional way of working on architect's offices since decades, although by a highly qualified draughtsman this time.

Traditionally, the dominant mode for discussing creativity and originality in architecture and in Free Form Design has always been that of intangible notions of intuition and talent, where stylistic ideas are pervaded by an individual designer, a "star designer," or a group of talented partners [Terzidis, 2003] That is why the computer, although already suitable equipped to function in another way than a sophisticated drawing machine, is still used in the Tradi-digital group cases as a drawing tool instead of a designing tool. The most prominent example of this practice is the case of architect Frank Gehry. In his office, design solutions are not sought through methodical computer-aided design methods but rather by the use of metaphors, allegories, or analogies. The design team spends countless hours of thought, modeling, iterative adjustment, and redesign based on the metaphor of a crinkled piece of paper. In this case it was the grand master Gehry who prohibited the computer application during the conceptual design. Calatrava is another example of an internationally recognized master who does not allow 3D drawings in his office. Frei Otto prohibited the computer to enter his institute in the 70s when modeling the roofs for the 1972 Olympic games of Munich. Eventually he was overtaken by the computer generation of German engineers. New technology outside of the scope of the master: a generation gap that is expected to disappear with the older generation.

The computer is then seen as a means for the draughtsman of complex structures primarily concerned with the technicalities of converting design ideas and models into digital geometries. Very little effort, if any in the Tradi-digital group, is concerned with the idea of using more sophisticated computer features for actually designing. A paradigm shift is not yet noticeable in this group of designers.

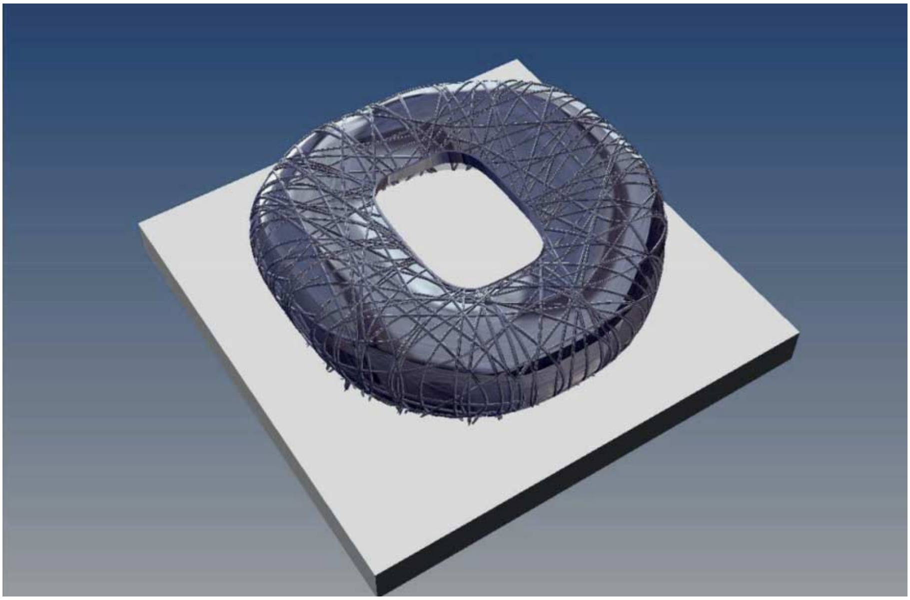


FIG. 115 Tradi-digital: Beijing National Stadium: Herzog & de Meuron.

SEMI-DIGITAL FFD

In the Semi-digital FFD way the conceptual formalisation of the FFD design find place outside the computer but the realisation of FFD find place with and within the computer.

This second group of Free Form designers, here called Semi–digital, are more or less aware of the possibilities which are given by the new CAD programs. Although they still think traditional about the design process they get inspired by the idea that the computer can manipulate their design (concept) very easily. They still stand with two feet in the traditional designing world and seem not yet really aware of the potentiality of the new CAD tools. Their use of the computer is reduced to deform, disturb and alter the overall order and organization of the buildings. Terzides (2003) distinguishes Caricaturing, Hybriding, Morphing, Kineticing, Folding (unfolding), Bending and Wrapping of forms.

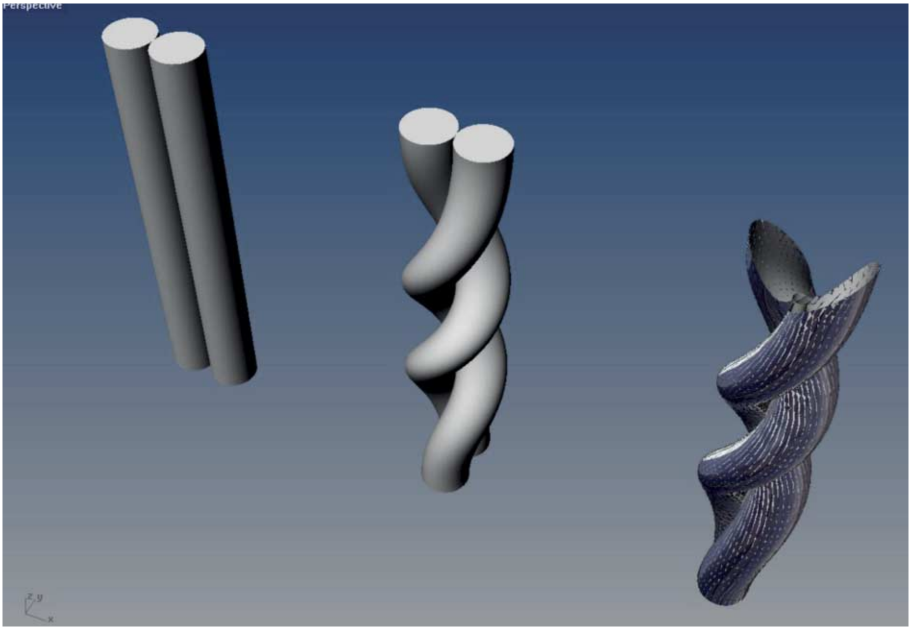


FIG. 116 Semi-digital : Cobra Towers, unknown, Kuwait

FORMAL-DIGITAL FFD

In the Formal-digital FFD way the conceptual formalisation of the design starts with and within the computer, and this integrated use of the computer goes on to the preparation drawings for actual realisation, too. In the Formal-digital FFD way the designer is still fully in charge of the designing process and of the subsequent steps of the process up to the end results (i.e. the final drawings).

Starting in the early 1990s, beginning with Eisenman's vision (Eisenman, 1992) and Lynn's curvilinearity (Lynn, 1995) and continuing through an overwhelming plethora of digital design studies, (Mitchell, 1990; Novak, 1994; Frazer, 1995; Lynn, 1999) architects have been primarily concerned with the formal manifestations of scientific theories using the computer as a medium of expression. (Terzidis, 2006) The problem with this approach is that it does not take in consideration alternative theories, concepts, or methods that are perhaps alien, foreign or even antithetical, but clarify the matter from other angles of view. This is still caused by the fact that architects have maintained an ethos of artistic sensibility and intuitive playfulness in their practice. The use of the computer as a formal tool and the increasing dependency of this group on computational methods have the risk for Whorf effects. The Sapir-Whorf hypothesis postulates that the nature of a particular language influences the habitual thought of its speakers. That different language patterns yield different patterns of thought. This idea challenges the possibility of perfect representation the world with language, because it implies that the mechanisms of any language condition the thoughts of its speaker community. This hypothesis emerges in strong and weak formulations. For the Formal-digital CAD users group this implies that a certain level of dependency on design possibilities of the used programs is dictated by the CAD language tools. So this group is almost unknowingly converted to the constraints of a particularly computer application style, e.i. computerization or even computation.

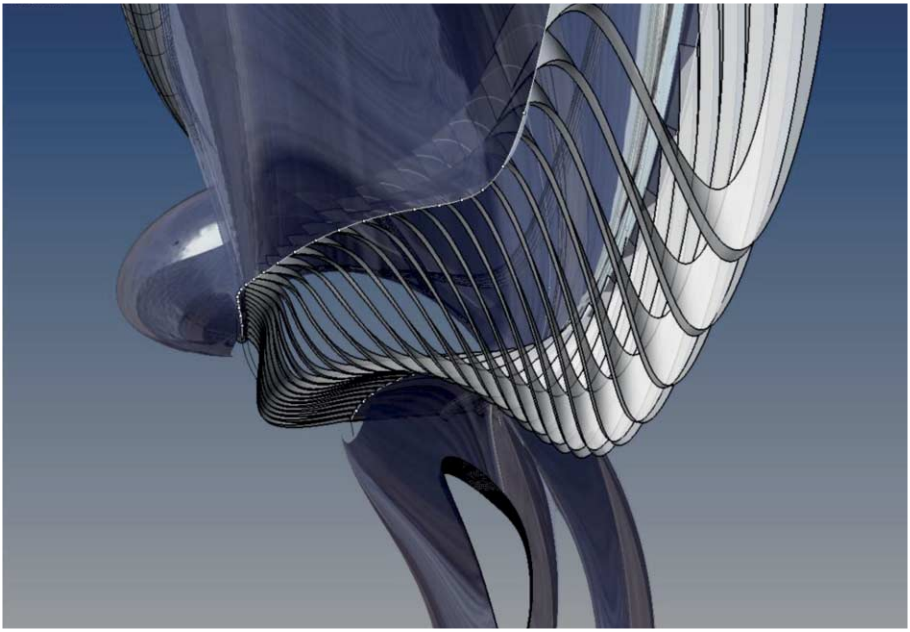


FIG. 117 Formal-digital, AA School, Victoria Goldstein, Xingzhu Hu, Ludovico Lombardi, Du Yu

TRUE-DIGITAL FFD

In the True-digital FFD way the conceptual formalisation of the design starts like the Formal-digital mode with and within the computer up to the preparation of the realisation too, but now the designer is only partly in charge of the designing process and hardly in the results of that process, because the designer creates only the borders in which the design process generate "its" own results. This can be recognized as Computation. The way the borders are created divide the possible results in the imaginable more or less expected results and the non-imaginable or even unexpected ones. The connotation 'serendipity' enters the scene here. This implies thinking and reflections about the paradigm shift of 'who is designing'. A paradigm shift is defined as a gradual change in the collective way of thinking. It is the change of basic assumptions, values, goals, beliefs, expectations, theories, and knowledge. It is about transformation, transcendence, advancement, evolution, and transition. While paradigm shift is closely related tot scientific advancements, its true effect is in the collective realization that a new theory or model requires understanding traditional concepts in new ways, rejecting old assumptions, and replacing them with new. Scientific revolutions occur during periods where at least two paradigms coexist, one traditional and at least one new and the frictions between them (Kuhn, 1996). The paradigms are incommensurable, as are the concepts used to understand and explain basic facts and beliefs. The two live in different worlds. The movement from the old or existing to a new paradigm is called a paradigm shift.

Traditionally, the dominant paradigm for discussing and producing architecture and the same is valid for FFD evaluation, has been that of human intuition, emotion, originality and ingenuity. For the first time perhaps, a paradigm shift is being formulated that outweighs previous ones. The design of True-digital FFD employs methods and devices that have no precedent. True-digital FFD takes the position that designing is not exclusively a human activity and that ideas exist independently of human beings, then it would be possible to design a computational mechanism which would associate those ideas. In either case, Computation can be seen as a purely physical phenomenon occurring inside a closed physical system called a computer.

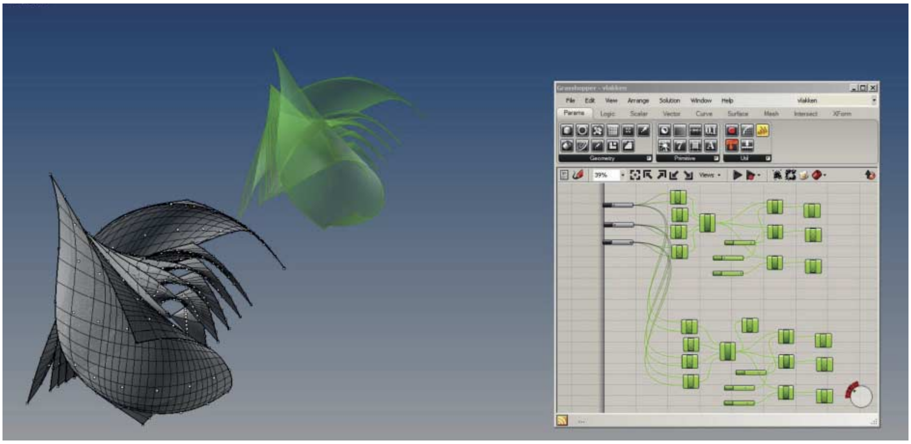


FIG. 118 True digital: AA School, Landscape project

10.03 DISCUSSION

Before it was possible to make an inventory of all existing methods for computer use in architectural design processes, it was necessary to study the general design methodology in architecture. As stated before architects are most often faced with ill defined problems and research has proven that their approach is also rather hap hazard-like. Therefore it is impossible to classify them as purely "descriptive" or "prescriptive" as defined by Cross (2004). Without a basic methodology to refer to in these architectural design processes defining a general methodology or set of methods would be an unrealistic task.

Furthermore as Roozenburg and Eekels (1998) claim; research methodology does not directly follow on design methodology as design and research strive for different results. Scientific research has to lead to generally obtained statements – in theory and laws – to declare and predict problematic issues. Design leads to material systems that have desired features and with that solve practical problems. Based on this assumption it seems not very logical, not to say impossible to start with a scientific methodological approach to come to insight in the practical design methodology.

These arguments led to the conclusion that classical methodology would not be a helpful conceptual tool for the architects involved, although it has its influences. Therefore a rather unconventional approach was used to organize the information and understanding of the processes involved. With the information from the literature research about the design processes of famous FFD buildings it became possible to reconstruct the actual design strategies and actions of those architectural projects and designs. In practice this meant that the buildings studied were all put into the relevant computer programs such as Maya and Rhino.

The results show that there may be differences in preferred models/programs, but the proponents of new models/programs of the design process all agree that there is a need to improve on traditional ways of working in design. One is the increasing complexity of modern design (new materials/devices (e.g. electronics). Many of the products, machines and buildings to be designed today have never existed before, and so the designer's previous experience may well be irrelevant and inadequate for these tasks. On top of this, the employment of this generation of computer programs is done by a younger generation of designers, who lack the design experiences of the older generation. From this lack of experience or better: absence of any design prejudice, revolutionary new approaches and results can be expected. But the profession is not easily convinced. Therefore it is argued that a new, more systematic approach is needed (Cross, 1998).

As the world of Design and so FFD is starting to shift from the "manual" model (Tradi-digital) towards the "computation" model (True-digital), a need arises to integrate two seemingly contrasting worlds, that of intuition and that of computation. What makes computation so problematic for design theorists is that it has maintained an ethos of rationalistic determinism in its field. This is the theory that the exercise of reason provides the only valid basis for action or belief and that reason is the prime source of knowledge. Because of its clarity and efficiency, rationalistic determinism has traditionally been a dominant mode of thought in the world of computation. In contrast, intuition, as defined in the art of design, is based on quite different, if not opposing, principles. Rather than to follow a rationalistic model, designers often employ the acceptance of empiricism, authority, spiritual revelation, metaphor or analogy as sources for their inspiration. More than ever now, as design intuition enters the computational world, a complement ring and harmonious mix of both processes is needed. This all leads to the idea that in the future one could even think of self generating design like in nature, although extremely interesting this is not the kind of research that has to be done at this moment.

So, because we are standing only at the beginning of a new design era in which designers are able to extend their thoughts into a once unknown and unimaginable world of complexity especially by computation, future research in that specific area of computation should be combined with the human factors such as: order, proportion, ornament, structure and scale. If not the quality of the architecture in special FFD will be ephemeral (short-lived) like the ephemeral state of computer technology.

10.04 CONCLUSIONS

Originally the role of computers in Free Form Design was to replicate human endeavors (Tradi-digital) and to take the place of human influence in the design process. Later the role shifted to create systems that would be intelligent assistants to designers, relieving them from the need to perform to more trivial task and augmented their decision making capabilities (Semi-digital). Today, the roles of computers vary from drafting and modeling to form based processing of architectural information, (Formal-digital) while the future use of computers (True-digital) appears to include a variety of possible roles. It is worth exploring these different roles in the context of providing an answer on the question: "Who designs? It is obvious that a combination of above approaches is more and more practical at this moment. Furthermore research into human factors in combination with computation should be studied.

10.05 REFERENCES

REF. 10.01 Achten, H. (2003), New design methods for computer aided Architectural design Methodology teaching
REF. 10.02 Aranda, B.L.C. (2006), Tooling. New York, Princeton Architectural Press
REF. 10.03 Cross, N. (2008), Engineering design Methods, Souterngat, Chichester, Wiley
REF. 10.04 Galofaro, L. (1999), Digital Eisenman, Basel, Birkhauser
REF. 10.05 Gausa, M. et al. (2003), The Metapolis Dicitionary of advanced Architecture, Barcelona
REF. 10.06 Hensel, M.M., A + Weinstock, M. (2004), emergence, London, AD
REF. 10.07 Hensel, M.M., A + Weinstock, M. (2006), Morphogenetic Design, London, AD
REF. 10.08 Hiller, B. (2007), Space is the machine, London, Space Syntax
REF. 10.09 Lynn, G.R.H., (1997), 'Animated form'
REF. 10.10 Lynn, G.R.H., (2002), Architectural Laboratories, Rotterdam, NAI
REF. 10.11 Oosterhuis, K.F.L, (2002), Architecture goes wild, Rotterdam, 010Publishers
REF. 10.12 Oosterhuis, K.F.L., et al. (2006), Game Set and Match, Rotterdam, Episode publishers
REF. 10.13 Reiser, U., (2006), Atlas of Novel Tectonics, New York, Princeton Architectural Press

REF. 10.14 Roozenburg, N.F.M. and Eekels, J. (1998) Productontwerpen, structuur en methoden, Utrecht, Lemma
REF. 10.15 Spuybroek, L. (2004), NOX London, Thames and Hudson
REF. 10.16 Terzidis, K. (2003) Expressive Form, New York, Spon Press
REF. 10.17 Terzidis, K. (2006), Algorithmic architecture, Burlington, MA
REF. 10.18 Zaera-Polo, A.A.M.F, (2004), Phylogensesis, Foa's ark Actar

11 MANAGEMENT OF COMPLEX FREE FORM DESIGN AND ENGINEERING PROCESSES

Mick Eekhout, Barbara van Gelder

The second half of the 20th century witnessed the development of a number of spatial and systematized lightweight structures: shell structures, space frames, tensile structures, cable net structures, pneumatic structures, folded plate structures and 'tensegrity' structures (Eekhout 1989). The main philosophy was to minimize the amount of material consumed. Computer analysis software provided the capacity for accurate analyses of complex geometries of the components in three-dimensional and (in our current view) highly regular structures. Thanks to the major upgrading of analysis programmes on personal computers, based on non-linear structural behaviour, the majority of regular 3D structures can now be designed without limitation. In the same period the material/labour ratio in the developed nations shifted, and the emphasis turned to reducing labour costs to help realise cost-effective structures. Hence, from a traditional point of view, the post-war adage of 'minimal material' became an intellectual target for architects and structural engineers, with less interest to clients and producers. Parallel to this much emphasis was placed on the development of project process management aspects, such as prefabrication, just-in-time (JIT) and lean manufacturing. Collectively, this has greatly influenced the choice of architectural style and structural building technologies. Over the last two decades structural designers have been confronted with spatial architectural schemes that have greatly benefited from computer-operated design and modelling programmes such as Maya, Rhino and 3D-Studio Max. These architectural designs are referred to somewhat interchangeably as 'free form', 'fluid', 'liquid', and 'blob' designs and consist of sculptural building forms in an arbitrary geometrical form that can only be generated or developed mathematically using sophisticated computers and software packages. Fluid building forms do not have a recognisable repetitive structure, unlike the majority of buildings, and place considerable demands on structural designers and contractors. For such buildings with tight tolerances and a high degree of prefabrication an enormous intellectual effort is necessary in the engineering phase to accurately define all individually shaped building components, thus helping to ensure a precise fit on the site. Indeed, the development of free form designs will transform traditional 'production' processes into 'co-engineering & production', which has implications both for architecture and the management of architectural, engineering and construction processes.

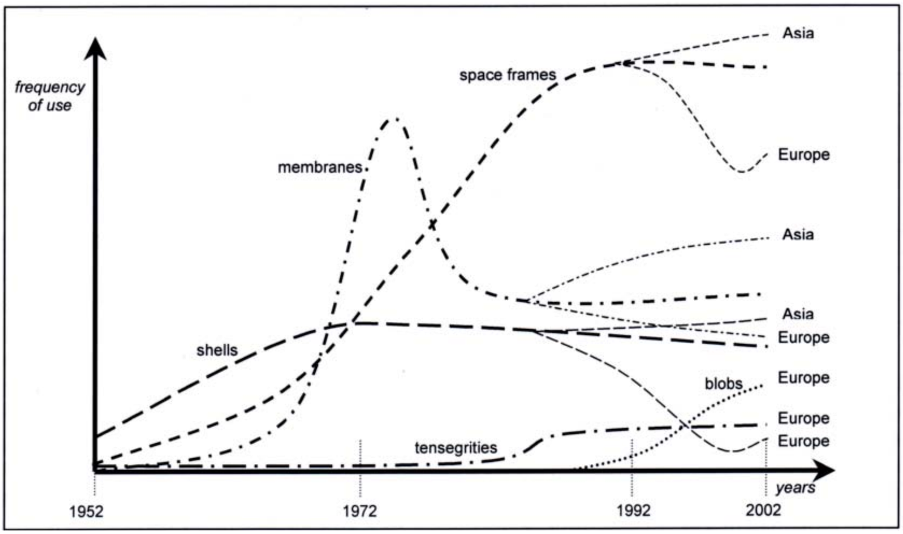


FIG. 119 Rise and Fall of Space Structures

The design of free form buildings does not follow conventional rules and requires a 'new' way of working to realise these creative buildings. At the conceptual design stage the difference between architects and structural engineers in handling the sculptural forms can be very wide. As the process develops the gap between architects and technical designers on the one hand and co-engineers, producers, co-makers, sub-contractors and builders on the other can also widen if the participants do not share the same ethos. Free form buildings demand close working relationships between the project partners and the ability to trust the abilities of co-partners in this highly creative, demanding and pioneering field of architectural design. Free form architectural designs would appear to fit the modern ethos of design management, which places equal emphasis on people, process(es) and product. This chapter provides an insight into the world of fluid designs based on experience of working with these innovative approaches via Octatube, an integrated construction firm located in Rotterdam, The Netherlands.

11.01 FREE FORM DESIGNS

The Guggenheim museum in Bilbao, designed by Frank O. Gehry and opened in 1997, was highly influential in bringing attention to free form design. Gehry first designs his buildings in clay as sculptures. The sculpture is then scanned to become a digital model in a geometrical computer programme. For this purpose Gehry's office in Santa Monica uses the French Dassault-based 3D-Catia programme, developed for engineering aeroplanes (Tomblesi, 2002). At this stage the geometry is fixed and the building is tendered as a total package. It is the main-contractor's task to hire skilled sub-contractors who are willing to engineer, produce and build the different components exactly as designed. Subcontractors must have the same software programme and appropriate skills in order to detail the geometry of their specific component parts. The construction and composition of all elements and components in the digital model, taken care of by different sub-contractors, is derived from the digital model supplied by the architects. This type of experimental, architecturally complex, geometry cannot be built by participants with different thinking (as is often the case), it requires precise coordination of work packages and effective collaboration between members of the temporary project organisation.

In free form designs the form of the components are non-rectilinear and non-repetitive. Computer rendering programmes like 3D Studio Max, Catia, Maya and Rhino are able to generate all kinds of geometric building forms, including the ones without any regularity in its geometric patterns. In the conceptual design stage, free form designing architects usually do not look for geometrical repetitive forms and systematized structural schemes or material behaviour. They design buildings like sculpting artists do in a totally new and creative way. Participating structural engineers are initially paralysed when they have to develop a load bearing structure in the contours of these geometrical forms in order to materialise the structural concept of the building's envelope. Often their knowledge is not automatically updated or geared to the new design challenge, which can hinder effective interaction. On the one hand engineers are forced to develop their flexibility in structural knowledge in action and on the other hand their 'soft' people skills need to be professionally developed. The same argument is also valid for the technical building engineers who carry out the detailed engineering of these designs to the level of shop drawings. The question is how to consolidate the 'computer supported sculpturalism' of the architect with the sound structural design and industrial prefabrication principles of the structural engineer. There are several driving forces behind the development of liquid designs. These include a generation of young 'digitised' architects seeking their own identity and architectural style; assisted by changes in technologies and approaches, from standardised solutions to bespoke, highly creative, buildings. This appears to be helped by a changing construction sector, from a producer dominated market to one in which the customer has a voice and a desire for better value (and one might argue more stimulating) buildings. In some cases the value to be gained from high quality buildings has also led to an increase in building budgets. Collectively these factors have helped to bring about rapid developments in free form buildings.

In general architects have become more flexible with the overall geometry of free form buildings. However, these non-rectangular geometries have to be fixed accurately by the project architect since there is no room for deviation (otherwise one component will never fit accurately to its neighbours). This type of building design and construction dictates a very close collaboration between the engineering, producing and building parties. One might speak about 'collaborative high tech' engineering and production. Mutual trust between collaborating parties plays an important role in the entire process, which is the opposite of the intrinsic suspicion inherent to the ad hoc selection of the open market tendering system. Inevitably this collaborative approach requires a different type of preparation and realization process, with closely collaborating parties.

11.02 INTEGRATION OF PROCESSES

Any change to the established way of designing buildings requires the support of the technology. In the scheme impulse for new architecture initiated on the right hand side of free artistic design can only be realized by developing new technologies. Depending on the characteristics of the innovation sometimes new fundamental research is required. In the free form scheme, architects act as sculptors, moving more to the right side of the scheme.

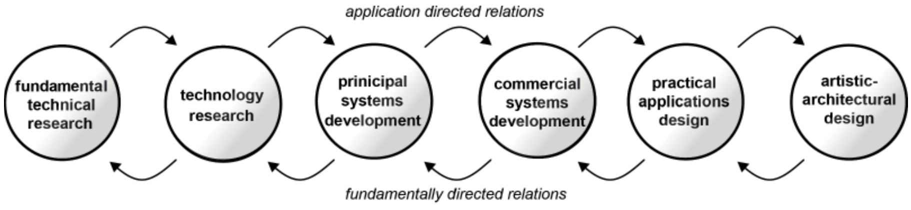


FIG. 120 Relation between fundamental research to artistic design

Octatube specialises in the design and build of spatial parts of buildings, mostly special components in roofs and façades. The philosophy is that free design and fundamental technical research are inter-dependent activities, which is applied within the office. According to recent design experiences and observations of the author, frameless glazing using tensile structures and sophisticated double glass panels were greatly stimulated by the development of UV-resistant glue. By using this glue it was possible to connect the inside of the inner pane of insulated glass panels to the outside surfaces of the (Quattro) spider connectors on top of the stabilizing cable structures. Without chemical technology and aeronautical engineering this (now) patented technology could not have been developed. Fluid designs are first of all material compositions with an unconventional geometry, whereby architects hope that the spatial composition will be the first and only derivation in the building cycle. A complicated geometry, however, requires complicated geometrical surveying in the design and engineering phase, in the production of individual building parts, and in the composition and integration of these on the building site. These mainly logistical processes are of concern for the project architect as well as for the main contractor and the co-makers and subcontractors. The process needs a uniting approach in order to realise the design.

11.03 ASPECTS OF PRODUCTION

Production of many of the curved building elements and components by their nature need an alternative means of production. It could be by casting of free material into a complex element form. It could also be by deformation of economical commercial plate materials into a 2,5D or 3D form. The 2,5 D element form can be developed from a flat plane, but for the formation of a 3D panel more rigorous formation techniques in temperature and pressure are necessary, like explosion deformation of aluminium panels and hot mould deformation of glass panels. The geometrical definition and fixation of these 3D elements will complicate the engineering of these elements greatly, but also the production and the fitting together of the collection of panels belonging to one building part. On top of this there is the joining of the different building parts, engineered and produced by different parties in the building: the building ‘seam’ and the building ‘knot’. So the decomposition of a geometrically complex building into elements and components to be made by different engineering co-makers requires an optimal description in the form of a computerized 3D-CAD mother model (described below) and another mode of operation between the co-makers with accurately agreed and maintained tolerances. In this respect it is of great importance to keep the hierarchy of building products in mind (Fig. 121) so that deformable materials and commercial materials are not confused with geometrically fixed liquid designed elements and components, to be assembled in the whole technical composition called building (Eekhout 1997).

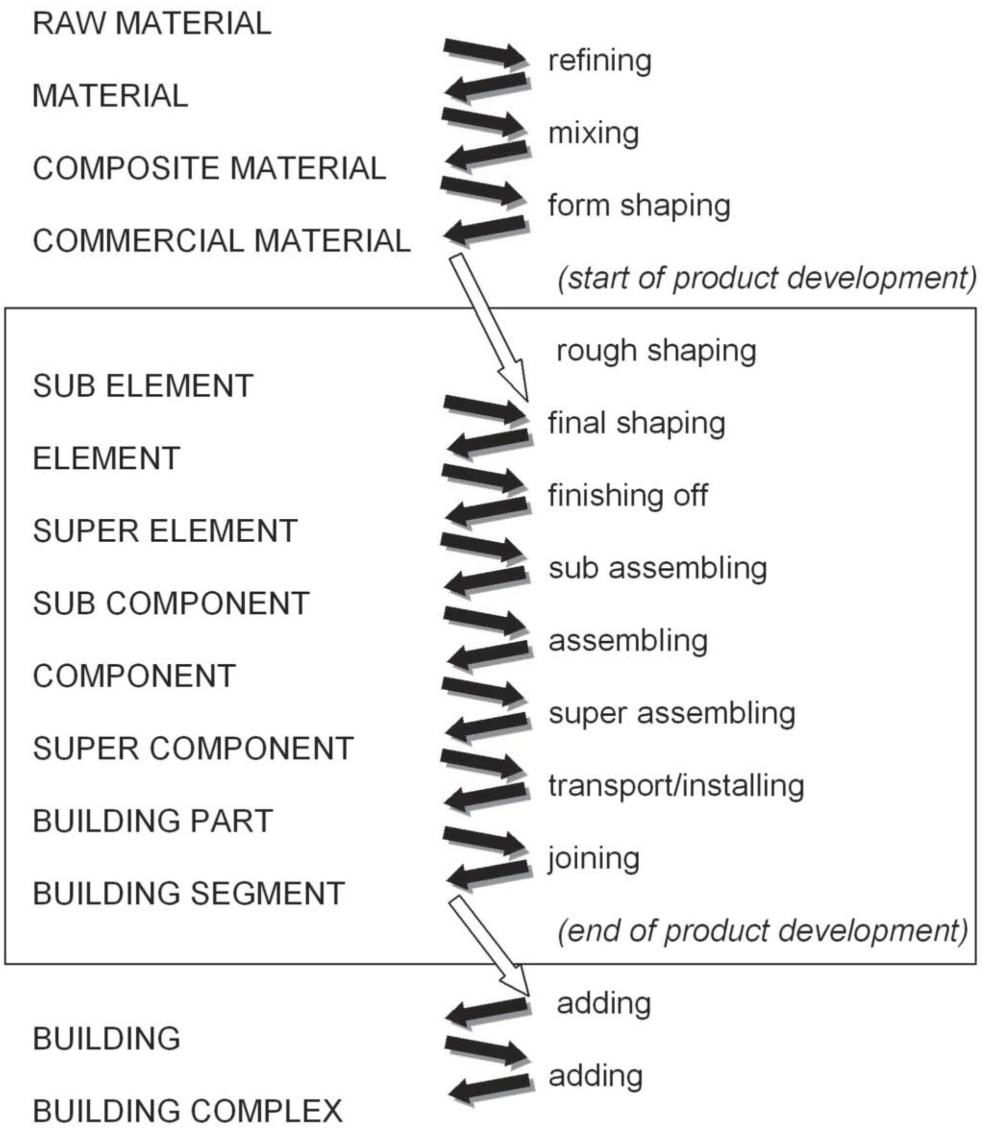


FIG. 121 Hierarchy of Building Products

11.04 TOWARDS A HIGHER DEGREE OF CO-OPERATION AND COLLABORATION

A free-form geometry involving all building parts of the building design leads automatically to a very close co-operation and collaboration between the partners in the building project. This is more intense and requires a change in attitude compared to more traditional processes, something that can take most architects, usually more familiar with maintaining some distance from construction activities, a number of projects to accept. The building team is configured as the sum of all participating architects, designers, advisors, main contractor, building managers, component designers, sub-contractors and producers involved. In the four stages:

- Design of the building and its components;
- Engineering of the building parts (elements, components and site parts);
- Productions of elements and assembly to components;
- Building on site and installation of prefab components.

Each phase has its own characteristics of design considerations and assuring quality of the building as the end product being a composition of the different building parts, installed on the building site by various partners. The first phase of design of the building and its components will be the domain of the architect and the structural engineer. The tendency is for standard products to become systematized and for building systems to become special project systems. The need for special components will increase because of the special geometry of the building, influencing the form and position of each composing element/component. The tendency towards individualisation can be described as industrialisation in lots of one, i.e. bespoke designs.

The design phase has to result in a 3D-CAD mother model of the building, (preferably drawn and maintained under the control of the architect). In this digital model the principal elements and component sizes and their principal connections need to be coordinated. From this model each partner will start their own co-engineering work. The architect must incorporate all relevant engineering data of all the components of the different building parts, each building part to be worked out by the different co-engineering members of the building team. The information contained in this virtual model develops quickly into a Building Information Model (BIM). This model will then be used for tendering purposes, although it is still common for information to be conveyed on paper drawings. A 3D model is inevitably part of the future as digital building information tools are introduced and become more commonly used.

11.05 SEQUENCES FOR CO-ENGINEERING, PRODUCTION AND INSTALLATION

All engineering activities have to be based on a central digital 3D-mother model accessed via the internet, which forms the digital base for the engineering of the total building. The keeper of the model is indispensable, maintaining the model and checking for consistency of use during the life of the project.

The free form projects described in these case studies are exemplary for the bottom-up driven development of 3D digital building information models by architects and design & build contractors, which has been going on for the past 15 years. Free form projects are, for the free form architects and for the building industry, the frontrunners for the introduction of building information models (BIMs) because the realisation of free form architecture can only be mastered through a digital, multi-party, collaboration process. At some point in the near future this development will inevitably meet the top-down introduction of BIM, and development of IFC standards and IFD libraries, which are born out of the aim for greater efficiency and are also an answer to globalisation of the building industry as they share mutual interests. The development of software certainly plays a major role in this process where the geometry driven free form architecture and the object driven development of building information models are to collaborate, although this still has some way to go before compatibility is achieved. For the co-ordination and integration of the different co-engineering parties in the building team two clearly distinct modus operandi could be followed:

Separate Model: Every participant takes the basic (geometrical) data from the 3D mother model and works on it in separate software programmes. Problems relate to checking the quality of the information, coordination, changes and modifications of 'separate' information packages. When two or more building parts join, each side has to be worked out by a separate building party and the joint has to be agreed commonly. Software packages have become compatible by the market entrance of IGES and STEP protocols in recent years. However, checking the different results is still extremely time consuming and mistakes only emerge on the building site. The architect does not check any drawing for its dimensions and commonly states on the drawings "dimensions to be checked at site". This traditional approach is not satisfactory for free form designs because it will easily cause confusion due to outdated information, mistakes, misalignments, disputes, failures and inevitably claims.

Engaged Model: When the architect would be engaged to keep a close watch on the 3D Model (BiM) a better involvement of all parties is expected. The question of the responsibility remains, however.

Collaborative Model: All participants work with the mother model. But this has to be controlled logistically. Each engineering party works on the 3D- mother model successively as it is allowed 'slot-time' (like aeroplane traffic coordination). During the start the situation is fixed and detailing and modifications of elements and components by each party can be fed in successively. All co-engineers get their turn in the sequence. The whole is to be worked through. The end situation will be fixed and communicated to all building parties. After the proper closing off of the slot-time of one party, check and certification by the model keeper, the next is allowed his slot time. Simultaneous work on the 3D model by more than one engineering sub-contractor is not allowed, as it will lead to confusion and possible legal problems. Gehry enforces the use of Catia in his projects. But different teams in the engineering department of one producing company could be working with different software packages, which may lead to errors and confusion. So a plea is made by the authors for the development and use by all participants of an universal 3D-computer package, capable of handling the conceptual design, the presentations, the overall building design drawings, the statical analysis, the engineering co-ordination drawings, the shop drawings up to the quantity lists. A system which is entirely applicable for buildings, and can be used during design, taking off quantities, costing, engineering, shop drawings, manufacturing and assembly, which is cost effective too. After each of the building-directed engineering contributions of all participants, regular geometrical checking has to be done. Neglecting this will lead to large problems in the integration and co-ordination of the engineering, in production and installation and hence, much effort has to be spent here. Liability is at stake here. Four building parties are able to execute this: the architect, the building technical engineer, the building contractor and the geodetic surveyor. Each option has its advantages and disadvantages. Each proposed party has to realise a sort of forward or backward integration. Also software is developed towards this goal of detecting overlap of elements in the mother model. There is an advantage for architects to seize this opportunity in order to gain back their position in the building process.

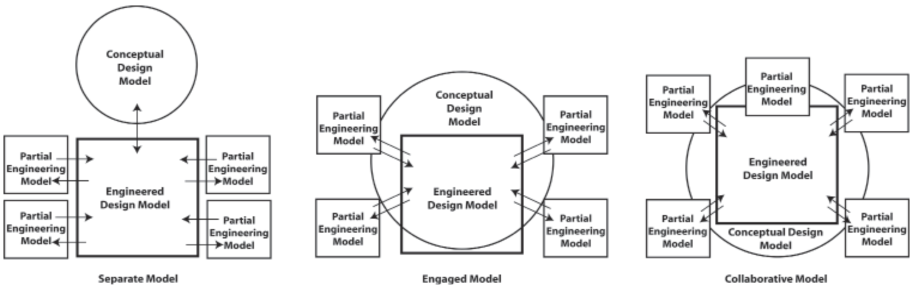


FIG. 122 The 2 extreme models: left 'Separate Model'and right 'Collaborative Model'show the position of the architect in relation to the mastership over the 3D Model with an engaged model in between

The data from the overall 3D-mother model or from the individual overall CAD models or drawings will have to result in the drawing of individual element drawings, in the form of shop or production drawings. This will be done direct in CAD/CAM for cutting, drilling, punching and machining operations, depending upon the development of each trade. Or it could be done via manual machine activities like welding and bending operations, casting of steel nodal pieces and assembly of elements into components, hot dip galvanisation and painting or coating afterwards and protection for transport to the building site. The engineering part of site activities are the installation/assembly/erection drawings which indicate the identification of the transported components and their location by XYZ co-ordinates. These points will have to be established on basis of the characteristic geometric points of the 3D-CAD mother model. It is the contractor's responsibility to establish these points during the progress of work on the site. Because of the complexity of the geometry and the absence of straight and orthogonal lines a new specialist has emerged, the geodetic surveyor. The geodetic surveyor makes pre-checks and post-checks of the positioning of the components on the site and is an essential role, without which the building could not be realised. After completion of a work package the surveyor will examine the click points on site with the theoretical ones and their tolerances. This is done in order to prepare and inform the next contractor who has to rely on the robustness and quality of work of earlier work packages. Participants are only able to compensate certain tolerances because production is completed before starting on site. The discipline of prefabrication and industrialization and the installation of subsequent trades will have to move in the near future to a discipline of industrialized complex building geometries. Too often, the building of liquid designs is approached with the same attitude as more regular buildings, where the irregularities of earlier trades are expected to be corrected or accommodated by later labour. But approaching fluid architecture in the traditional way will result in disputes and bankruptcy of the weaker parties. Although it seldom happens, tender documents should contain the most effective modus operandi and respective procedures and relationships to obey. Engineering needs to be the core of the process.

11.06 CASE STUDIES

The case studies briefly described below are based on the experience of Octatube. The intention is to describe, explain and highlight a number of issues relevant to the design and management of liquid designs, charting early setbacks and more recent successes.

CASE 1: METRRO STATION WILHELMINAHOF, ROTTERDAM

The first of the Dutch blob designs was designed by Zwarts and Jansma in the mid 1990s for a glazed hall covering the underground railway station crossing a tramway in Rotterdam-South, known as the Wilhelmina-pier. The design of the main structure contained a number of steel tree-like supports with branches of varying thicknesses and heights, which were covered with an undulating glass roof. The architects and the engineering firm ABT had devised a nodal system to suit the many different corners in which the glass panels had to be fixed. Octatube proposed an alternative node which would enable the steel riggers to accurately position the tops of the steel rods supporting the glass nodes. This alternative also included a logistic modus operandi for the continuous 3D surveying of all installed components, adjusting them to the exact level and X,Y,Z position. The design and engineering approach was set up according to the above mentioned Separate Model. Although Octatube won the tender with the lowest bid, the main budget had not allowed for the complexity of the design realisation, which subsequently led to a change of architects and engineers. Thus the experimental and highly complicated structure was not realised, much to the disappointment of the architects and engineers (Zwarts et al. 2003, Nijsse 2003). On reflection, this elegant, but technically difficult roof, deserved a pre-engineering contract with a specialist-contractor, a full-scale mock up and a more realistic budget. Eight years later a similar structure was realized for the Zlote Tarasy Shopping Centre in Warsaw (Jerde Partnership), made possible by improved knowledge and experience.

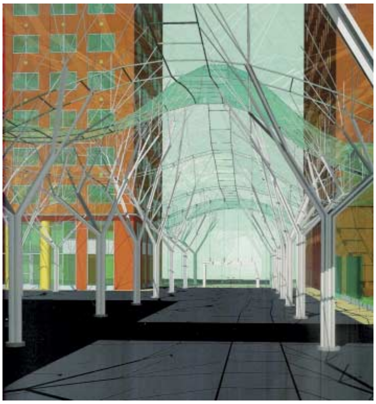


FIG. 123 Galleria Wilhelminahof, Rotterdam

FIG. 124 Zlote Tarasy, Warsaw

CASE 2: DG BANK BERLIN, OCTATUBE'S DESIGN ALTERNATIVE

Gehry was responsible for the design of the glass roof over the D.G. Bank in Berlin. Octatube was involved in the tender phase. The design called for a triangular network in the form of the body of a whale, to be constructed in stainless steel solid square rods, in triangulated form, to be covered with double and triple glazed panels. The nodes were designed in finger form with all fingers having different vertical and horizontal directions. Octatube's alternative proposal consisted of hollow spherical cast nodes and tubular CHS members in stainless steel. The nodes were to be drilled in the exact direction. The length of the tubes would form the desired spatial envelope. The architect opted for the original design and the tendering process resulted in a contract for Gartner. Their tender price turned out to be too low and they were subsequently taken over by Permasteelisa, completing the building to a high degree of accuracy in 2000. The design and engineering approach was set up as the Engaged Model of Fig. 122. The management lessons learned from this project are the blight of many traditional approaches, in that an extremely low tender price for the building created problems for the contractors. Although Octatube were not awarded the contract, the knowledge gained from entering the tender process was taken forward to new projects.

CASE 3: MUNICIPAL FLORIADE PAVILION, HOOFDDORP NL

The winning competition design by Asymptote Architects, New York, contained a building volume in an arbitrary form with two sloping glass surfaces. In a later planning phase this glass roof was partly replaced by aluminium panels. Water continually runs over both roof surfaces, known as the Hydra Pier, a reflection of the Dutch water-rich culture. The design and engineering approach followed the scheme of the Separate Model of Fig. 122. There are three remarkable technical experiments in this project. The first consists of the water filled continuous curved and frameless glass pond. The target for development was to realise the laminated glass panels in 2D, 2,5D and 3-D glass frameless suspended glass. These panels were 1 x 1,4 m in size. The (still to be realised) challenge of production was an experimental route of an initial thermal dual deformation into a 3D-form, subsequent (certified) chemical treatment, liquid lamination of the duo panels, testing these and comparing them with the theoretically calculated end results. Due to high costs and long replacement time the client chose polygonal flat panels of laminated 12-12-4 fully pre-stressed floatglass. The second experiment contained cold deformed laminated glass panels, produced flat and bent by first fixing them on the four corners like the habit for spider glass and pressing two double points pushing outward on the upper and lower chord of the 2 x 2 m^2 glass panels. The cold bent camber achieved was 80 mm over 2 m side lengths. The cold bent panels had to be combined with hot bent monolithic panels for the smaller curvatures. The third experiment were 3D aluminium panels in the two outer corners of the roof. To this end an experimental route was followed of drafting a Maya file CAD/CAM, machining polystyrene blocks to the desired mould shape, smoothening them with epoxy filled glass fibre weave, cast off with fibre reinforced concrete. After curing, the concrete mould was covered with 5 mm aluminium sheet, in a 300 mm water basin. After this global forming, the edges were checked on a timber model, the edges were fitted and welded on and the panels were smoothened and coated by air spray. The fitting on the site and sealing the 10 mm gasket in between finalised the production and installation of these 14 panels. Industrialisation in lots of one.

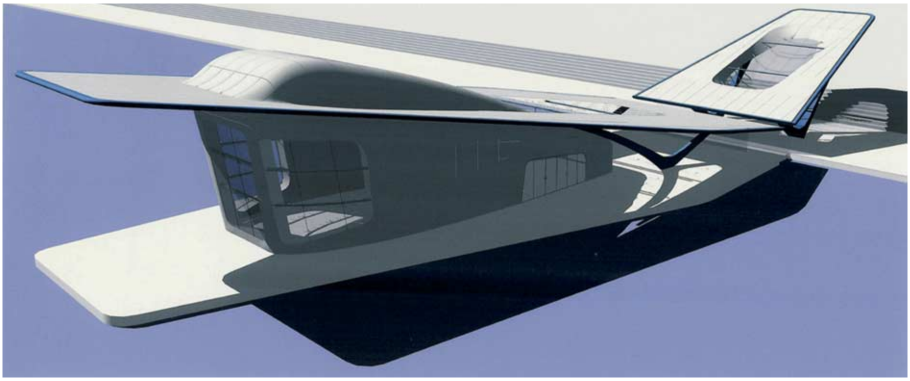


FIG. 125 Overview of the Municipal Floriade Pavilion, architects Asymptote

The management lessons learned in this project related to communication between the project participants. The architects set up a virtual office on the internet to allow participants to exchange project information, such as models and drawings. Unfortunately, the information exchange did not work as anticipated because of a lack of regular communication between participants and a lack of interoperability between different software packages used by the different parties. (The architects used Microstation, the engineers used X-Steel and Octatube and Van Dam worked with different versions of AutoCAD.) It became evident during the design and engineering process that there was no one partner assigned to verify and co-ordinate the dimensions and details in the drawings created by the different sub-contractors, which had consequences. For example, there was a dimensional, positioning difference of 125 mm between the glass panels produced by Octatube and the end position of panels made by another contractor, Van Dam. With the benefit of hindsight it is evident that not enough time was devoted to establishing appropriate communication channels and protocols for data exchange. So the first blob building to be realised in the Netherlands unwittingly helped to demonstrate the inadequacies of the traditional infrastructure when applied to complex free form designs: which required precise coordination and clear direction in the engineering process. It also became clear on this project that 'uniform' engineering software is an absolute necessity to allow 'collaborative engineering'. This is an alternative approach to concurrent engineering, the difference being that in collaborative engineering there is real cooperation and exchange of information.

FIG. 126 Cold deformed glass panels in the South facade

FIG. 127 Glass pond at the entrance of the Municipal Floriade Pavilion

FIG. 128 Roof panels created with Exploform technique after installation

CASE 4: FRONT FAÇADE TOWN HALL ALPHEN A/D RIJN, NL

Architect Erick van Egeraat and engineers ABT produced a true liquid design, since the main load bearing structure contains no repetition. Octatube was selected for the engineering, production & installation of the frameless glazing façades. The overall design and engineering approach chosen was the Engaged Model of Fig. 122. This building has a façade of frameless glass panels, fully screened with graphical motives of trees, leaves and flowers in an ad hoc fashion. The panels are supported by elliptical façade mullions up to 20 m high, spaced at around 1,8 m, with glass support nodes in between. The glass panels, around 850 in total, are all unique in form and print design. The glass panels have been screened on surface 2 and have a low E coating on side 3. Most of the panels are 10/12/10 double glazed units in fully-tempered clear glass panels; the roof panels have laminated lower panels. All panels are fully tempered. Because of the geometrical differences between lining of the façade mullions and glass panels, the columns are positioned in varying angles to the glass panels. The glass connectors are irregular. Not one of the 90 mullions is equal to another. In the anticlastic formed surface (roughly 10 x 10 m²) the rectangular glass panels are twisted and the elliptical mullions have up to 9 bends in their longitudinal axis, which are cut and welded on jigs in the factory straight from the engineering drawings. The secret behind the fit of the system was the engineering prior to the prefabrication and the continuous topographic checks by the geometric surveyors on the site. At the double curved back of the building approximately 500 non-rectangular glass panels are installed within the random form of the intersecting bays. A timber window firm first tried to develop stepped glass windows and suitable details, but gave up. Octatube's solution was to eliminate the window frames and to use only double glass panels composed of two panes of fully tempered glass, laminated in panels. The individual insulated glass panels were designed to be slightly warped by using cold form deformation. Tests in the Octatube laboratory showed that this was feasible and the stresses in the sealant were also acceptable, allowing the sealant manufacturer to provide a guarantee. The management lessons learned in this project related to the amount of time required for coordination. This type of liquid architecture was very demanding, consuming triple the time compared to a traditional project. Many problems with the coordination of other building parts appeared during the course of the project. For example, the tender drawings indicated details that were too simple, resulting in a hectic pre-engineering phase of nine months between tender and the acceptance of the contract. This also resulted in an increase of the project budget by 25% due to the complexity of the building façades. There was no real leadership of the coordination process during the project and it was only after the tender stage that the parties started to collaborate to resolve the coordination challenges and thus move into the engineering work packages. Overall the amount of designing, engineering and coordinating hours of all building team members amounted to 35% of the total project cost, about 3 to 4 times higher than the average contract for a traditional design.

FIG. 129 Front façade of the Town Hall of Alphen a/d Rijn

FIG. 130 Detail of the warped Front façade of the Town Hall

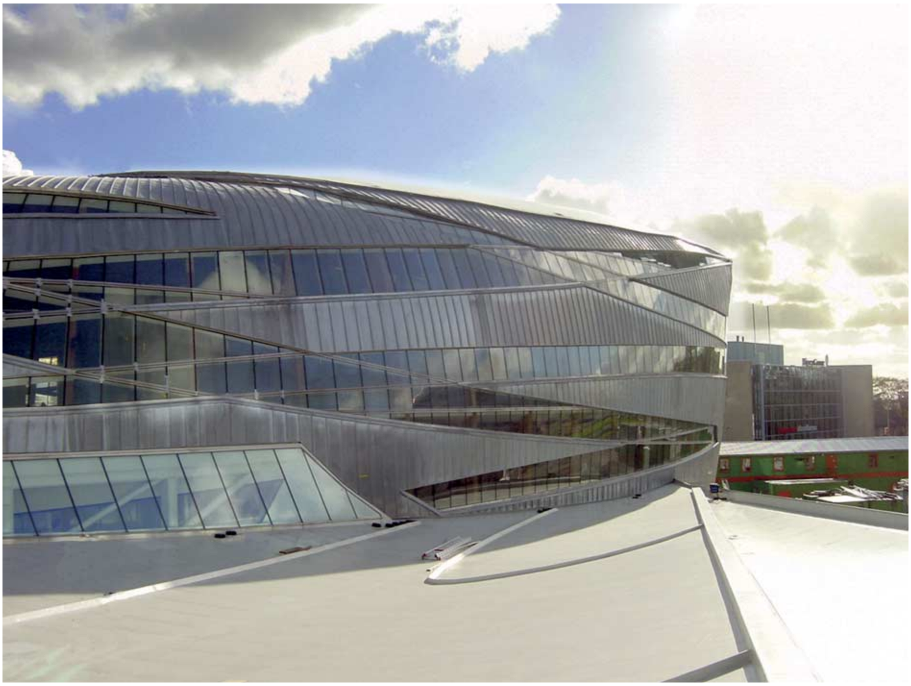


FIG. 131 Back façade with cold twisted "spaghetti strips of glass"

CASE 5: RABIN CENTER, TEL AVIV

Architect Moshe Safdie designed a memorial building for Yitzhak Rabin with two special halls on top: a Library and a Great Conference Hall, overlooking the Ayalon valley in Tel Aviv. The shape of the roofs resembles the wings of a peace dove. The tender, elaborated by ARUP of New York, contained a random steel structure with open profiles and a concrete cladding to be constructed at the initiative of the sub-contractor. Octatube's tender proposal included an alternative design for both, consisting of a better systematized space frame and GRP covered foam cladding on top as a variation to the tender specification, and a creative alternative idea of a load-bearing structure of a mega-sized GRP sandwich construction. This alternative would be able to span the 30 x 20 m^2 wings, although it was 25% more expensive than the original design, but a clean and structurally very straight forward construction. Octotube received a pre-engineering contract which contained a redesign in Maya of the design of the Great Hall in its overall design and its details. Octatube also made four full size material prototypes of the two alternatives. As a result of this pre-engineering contract, the prices dropped considerably. The management lessons learned in this project related to control of the engineering processes. The design and engineering approach was the Collaborative Model of Fig. 122. It was agreed with the architect that Octatube would be solely responsible for the redesign on a 3D-model in an appropriate computer program (Maya), the engineering (in AutoCAD with Pro-engineer) and the necessary productions, assemblies and installations on site. As a result of the knowledge gleaned from previous project failures and successes, it was anticipated that this would be a successful management approach, which proved to be the case. Octatube was supported by the architects throughout the process, but retained a critical stance regarding design quality. All design and engineering was undertaken at Octatube's offices, and the architects visited the office a number of times to discuss critical engineering phases face-to-face. This proved to be effective for discussing and resolving challenges at the detailed design phase.

FIG. 132 The Library just after installment of the composite sandwich roofs in November 2005

FIG. 133 The Great Hall just after installment of the composite sandwich roofs in November 2005

12 CURVED AND TWISTED DELTA RIBS IN FREE FORM TECHNOLOGY

Martijn Veltkamp

12.01 INTRODUCTION

In the design of structures for Free-Form building designs, the geometrical phenomena of curving and twisting often appear together. When such structures are built from linear members situated close to the building skin, the member's orientation relative to the skin is different at every position. Curving is the deviation of a straight line that occurs when members follow the building envelope's curvature. Twisting is the rotation of the cross section around the members' central axis, and occurs if structural members need to span between two surface normals that are not in the same plane. The surface normals are orthogonal to the surface, and they are only in the same plane if they are parallel, or intersect. Spherical surfaces are regular surfaces where all surfaces normals go through the centroid of the sphere, however in Free Form building designs, surfaces are arbitrarily defined and not necessarily decomposable in spherical parts. Material realisation of a twist is problematic because of the required force and the low geometrical control of the operation. In the case of steel structures this is a paradox: in the fabrication stage significant forces need to be applied to permanently form the members to the desired geometries, often involving stretching the material and not just bending. Once in use however, the members need to be sufficiently stiff and strong to fulfil their structural purpose.

12.02 STRUCTURAL MEMBERS

In the design of structures, the problem of curving and twisting is well known and has been resolved in various alternative ways, each with its own advantages and disadvantages in terms of geometrical accuracy, aesthetics and cost. Existing solutions are often trade-offs between these criteria. Using a case study design to compare potential solutions and test their performance, the aim of this research was to design a structural system that was structurally efficient, geometrically versatile and cost-effective. The case study is the DO Bubble, which is a Free-Form building design. The DO Bubble is a design by Aukett Architects (since 2006: Group A - Aukett), resembling a 50 metre long mannequin lying horizontally, supported on four columns: one under each 'shoulder' and two under the 'hips' (Figure 134). The volume is to be filled with three floors of leisure or sport functions, and for this to be equipped with daylight openings. When the architects came to the Blob Technology Group at TU Delft in early 2002, they had no idea on how to technically realise this project. The proposed building design featured all characteristics of a blob design:

- on a global level of scale its shape double curved;
- it is irregularly shaped, possessing a large variation of single and double curvatures (both synclastic and anticlastic), see figures 134–137;
- the shape lacks reference to a structurally optimised shape.

These made this building design an ideal case to develop alternative structural systems for, and map them to. Common to all building shapes was a thick-layered building envelope of variable thickness to place a structure within. No supportive structures outside this structural hull are considered. Neither the building bridging between the supports, nor the floors and its load bearing structure were considered as generic characteristics of Free-Form building designs, and have subsequently not been studied. In this research, the DO Bubble acts as a case needed to provide a context to the implementation of structural systems, as it is unnatural to judge their merits in isolation. This context consists of the intended Free-Form building shape and a technologically challenging structure inside. While this building design was never realised and therefore was not exposed to the real-life context of building design, the use of a case study was judged to be more appropriate than a study on design-details only, as if it were a conditioned laboratory experiment.

FIG. 134 The DO Bubble, a 50 metre long, three storeys high Blob-design. Images courtesy Aukett Architects

FIG. 135 Digital model used as template for test-implementations

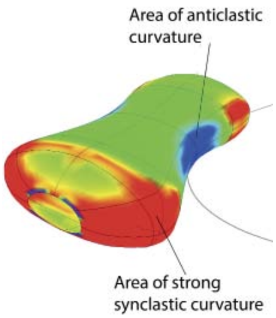


FIG. 136 Gaussian curvature analysis of the building envelope.

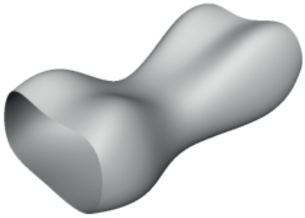


FIG. 137 Alternative model with stronger curvatures to test building systems in more extreme geometrical conditions

12.03 CURVED AND TWISTED STRUCTURAL SYSTEMS

A wide variety of curving network structures using nodes and members has already been built. To provide a support for panels on top, for instance glass panels in case of transparent coverings, the members are usually straight. In such systems, the twist is realised in the connection between the member and the node. Stephan et al. describe and compare a number of such systems in [Ref. 12.02]. When using spherical nodes in combination with members featuring rotational symmetry, the twisted transition from the member to the node remains unnoticed as it is incorporated in the member's symmetry. As far as the structure is concerned this is very advantageous, however the positioning and fixing of cladding panels on top is ambiguous. Alternatively, in the steel structure of the Web of North Holland (by ONL Architects, [Ref. 12.01]) steel sheets rather than standard profiles are used. As the sheets can be cut to any shape, they can follow the building envelope. The twist is created by folding a steel sheet across its diagonal, see Figure 138-140.

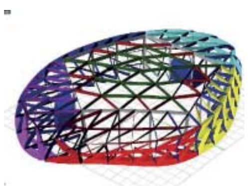


FIG. 138 Digital model of the Web of North Holland: a steel sheet folded across its diagonal. (Image courtesy ONL Architects)

FIG. 139 The primary structure consists of planar frames

FIG. 140 Twisting web member spanning between primary frames: a steel sheet folded across its diagonal

The steel structure of the Web of North Holland was designed by ONL Architects. Originally built as temporary pavilion, then reconstructed in 2006 at the campus of TU Delft. Also in steel structures, folded sheet-like elements have been applied in three-dimensional applications in the square-section backbone of roller coaster tracks by the Swiss fairground-design firm Bolliger & Mabillard (Figure 142), which are structurally far more performing than single sheets. Furthermore the box-section has a high resistance to torque, which also makes them suitable for space curves. Conventional rollercoaster tracks are made out of tubes (Figure 141) that are rolled in two directions to achieve the 3-dimensional curvature, requiring intensive labour to achieve the required high accuracy. Both tubular and square-sectioned backbones feature a constant exterior size along the track, although in the latter case this is not a constraint of the system. A larger cross section would result in a higher moment of inertia, and therefore provide a larger bending stiffness and thus lower stresses. In the case of tubes however, given the limited number of wall-thicknesses available, connecting tubes of different diameters would result in complicated joints.

Still describing a curved shape, but through curved rather than polygonal surfaces are the frames bearing the canopy of the Beurs-shopping area in Rotterdam (the Netherlands), see Figure 143. Here, two curved surfaces are structurally connected, thus creating a V-shaped cross section, with a curved upper and lower contour. However, since the frames are symmetrical, they do not allow for any twist.

FIG. 141 Tubular rollercoaster-track with 3D-curved backbone. (Image courtesy www.coastergallery.com)

FIG. 142 Square backbone of a roller-coaster-track constituted out of folded segments, with the folds accentuated. (Image courtesy www.coastergallery.com)

FIG. 143 Curved triangular beam in a canopy of the 'koopgoot' in Rotterdam (NL). Architect: Architecten Cie

12.04 DELTA RIBS AS A NEW SYSTEM FOR CURVING AND TWISTING

Numerous structural systems exist that allow for curving and there is also a limited number of systems available that allow for twisting. At the time this research was conducted, the number of systems allowing both curving and twisting, and which also possess a sufficient structural performance, was limited to rollercoaster-like structures only. Further requirements concern the system's structural capacity, which should be customisable to respond to the local structural solicitation. To anticipate a cost-effective application, preferably existing manufacturing techniques should be used, this way avoiding investments in new technology. Furthermore, the system's implementation has to be facilitated through a continuous walkthrough from design via engineering to production and assembly. To allow for such a customised implementation, all system's conditions, rules and degrees of freedom have to be made explicit. Earlier research on each of these aspects showed the potential of steel as structural material, with a wide range of fabrication methods and modelling tools supporting this. For the Delta Rib structural system steel was the material of choice, and it meets all requirements.

The primary driver of the Delta Rib-system's development has been to apply curved steel sheets in a customisable manner. By using curved sheets the formal language of the structure would be that of the overall building shape itself. All curved surfaces had to be developable (= to unroll to a plane through bending only, and no stretching) as they were to be fabricated from initially planar steel sheets. This way it was also assured that the geometrical definitions would be precise, without any approximation to be made during the (digital) unrolling and (material) rolling.

Curved surfaces could either be cylindrically or conically curved (Figure 144). As the latter have more degrees of freedom (namely non-parallel ruling lines), which is useful to shape the ribs to the needs of the architectural or structural designer, the conical curvature was opted for. Next, a choice was to be made between a single cone and multiple cones (Figure 145). Research into formative techniques led to the conclusion that surfaces constituted out of multiple cones could not be formed on a large scale using existing techniques, despite the latter having far more degrees of freedom. Already the simple transition from convex to concave would be problematic: existing tools could only exert bending in one direction, and the convex-concave transition would require a tool on both sides of the surface during the bending operation, or otherwise removal and re-insertion of the object. The next formal constraint to decide upon was the permitted variation of curvature, for which a single constant curvature was opted. For this not the technique of rolling was decisive, but the ability to verify the rolled shape's geometry. Each curved element was now part of a conical surface, of a cone with a circular base. Verification of the geometry involves checking that the curvatures are of constant radius.

Despite the rigorous narrowing down from all developable surfaces to cones of a single constant curvature, still a wide variety of ribs, as shown in Figure 148, could be designed with these.

The considered techniques for curving steel sheets into various curvatures are listed in Figure 147. Applicable to all curved shapes, manual cold bending is by far the most versatile, however the maximum sheet thickness is constrained such that its application is limited. Computerized Numerically Controlled (CNC) rolling does exist but suggests automated production, whereas this is only true for one-direction processes (without monitoring the created geometry). Due to the springback of elastic material it is difficult to calculate the required force, and CNC-rolling may be applied successfully, but in larger series only where the first 5 to 10 pieces are used to iteratively find the right settings. For one-offs, the technique is judged not yet mature, which also counts for laser forming.

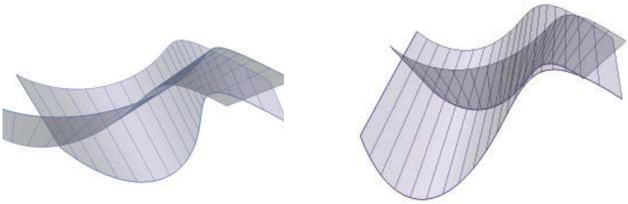


FIG. 144 Ribs with cylindrical (left) or conical (right) surfaces.

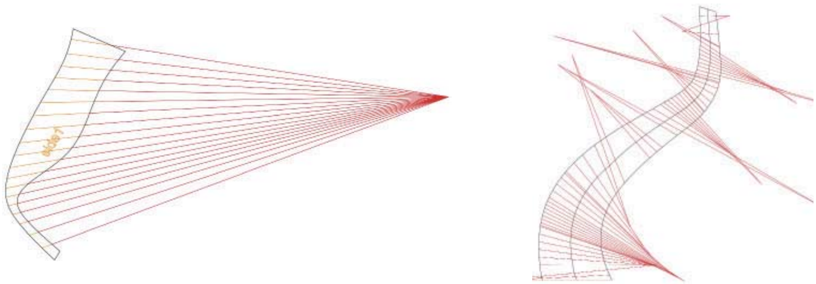


FIG. 145 Conically curved surfaces consisting of a single cone (all ruling lines through one point, left) and of multilpe cones (ruling lines intersecting in multiple points, right).

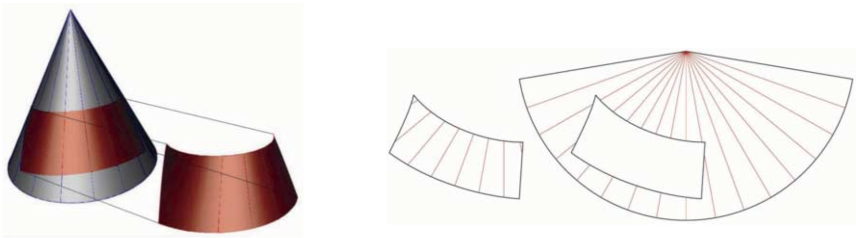


FIG. 146 Three-dimensional shape and unrolled pattern of a constant conical curvature.

Formative technique → / ↓ Type of curvature	Manual cold bending	CNC rolling	CNC laser forming	Cold rolling
Either constant concave or convex curvature	Possible	Possible	Possible	Possible +
Either non-constant concave or convex curvature	Possible	Possible	Possible	Not possible
Both non-constant concave and convex curvatures	Possible +	Not possible	Not possible	Not possible

Key: Possible technique for realisation | Not possible | +: most appropriate

FIG. 147 Techniques for curving steel sheets and their field of application.

12.05 THE DELTA RIB STRUCTURAL SYSTEM

Delta Ribs are structural members consisting of three curved steel sheets connected along the edges, applied in a network (Figure 148 and 149). The network consists of n-cornered shapes, lying on an irregularly shaped curving building envelope, at which in each corner three ribs connect in a network node. From each of these nodes an offset is made normal to the surface (this way fixing the depth of the three ribs meeting in this point), as well as sideward (to fix the points where the adjacent sides of two ribs meet). Now, each original network-node has been replaced by four corner points. Next the three conically curved sides defining a rib will be generated. All engineering is to take place on digital models of zero thickness, thus using a surface representation. This model is enriched with structural or fabricational information as the model is becoming more detailed.

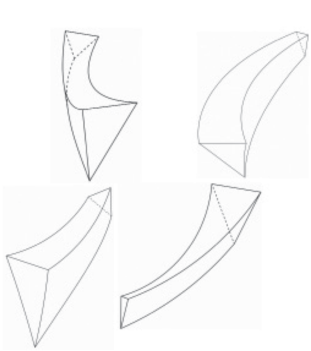


FIG. 148 Variety of Delta Rib-shapes

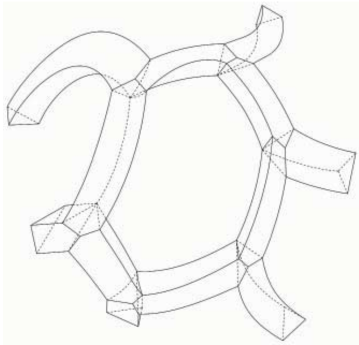


FIG. 149 Delta Ribs assembled into a network configuration

Between two of the four corner points the designer draws a ruling line. Next, a cone is constructed of which the cone top is lying on the drawn ruling line, whereas the remaining two corner points both lie on their own ruling line also going through the cone's top. Next, a circle is drawn through three points, all on one ruling line and at the same distance from the top. This circle becomes the ground-curve of the cone. As its top was already fixed, the cone is now entirely defined. The actual position of the cone's top is a degree of freedom, allowing the designer to slightly adjust the strength of the curvature. This surface-generating procedure is now repeated for the remaining two surfaces, after which all exceeding parts can be trimmed away, and only the Delta Ribs remain. The three surfaces of the ribs are now unrolled to a plane where further detailing is done in a 2D workspace: anticipating the cutting of the steel sheets, the subsequent rolling, and markings needed for both rolling and the subsequent welding. Now that the rib's geometry is known, so are the mechanical properties needed for structural analysis and optimisations resulting from this can be carried out. Analysis can be applied to linear members with equivalent stiffness properties for bending in two directions as well as torque.

12.06 STRUCTURAL EFFICIENCY THROUGH FOUR WAYS OF CUSTOMISATION

Delta Ribs can be customised in the following ways, this way tuning their structural properties: **Customisable triangular cross section**. The geometrical freedom of defining a rib between two sets of three points arbitrarily positioned in space not only allows Delta Ribs to incorporate a twist, it also permits the ribs to vary their cross section from one extremity to the other. Thus, the triangular cross section at one end is neither a copy, nor a scaled version of the cross section at the other end. The rib's cross section can be optimised further to the applications' needs by introducing additional elements in the rib's cross section.

Strip-flange. A strip, especially those of considerable thickness, enlarge the rib's bending capacity by adding material at the perimeter, see Figure 150. The strip should be planar since this greatly facilitates positioning of the curved parts during fabrication. Planar strips are achieved when the plane is the plane of symmetry between the two curved sides connected to it or when the strip's edge is a planar arc; the planarity assures that the strip is planar, the arc assures that the sides are parts of cones. Like the addition of a tube in a rib's edge as described in the next section, the strip is conceived to be inserted only along one edge, this way keeping the formal freedom of the rib's remaining two edges as much as possible unconstrained.

Tube. Like the strip, a tube is inserted along a rib's edge to increase the rib's structural capacity (Figure 151). To apply curved tubes of constant radius, the rib's edge has to be circular. The structural contribution to the rib's performance of the tube is determined by its diameter and wall thickness. The tube's exterior diameter affects the geometry of the adjacent sheets, while the tube's wall thickness does not. Furthermore, smooth transitions from one rib to another can only be made when only one tube diameter is applied, this way keeping the wall thickness as a degree of freedom for final optimisation.

Sheet thickness. The sheet thickness of each of the three curved sheets which constitute a rib is to be determined individually. In case of an inserted strip or tube, the cross section of the sheet opposite to the enforced edge is to be balanced with the cross section of the inserted part, such that the internal lever arm is used most effectively. Increasing the sheet thickness also prevents sheet buckling.

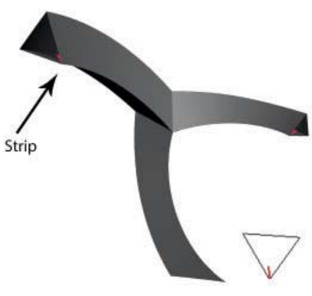


FIG. 150 Addition of a planar strip, requiring the edge to be planar

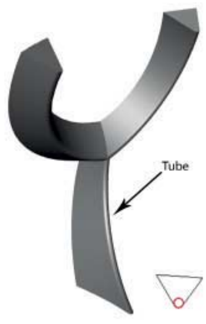


FIG. 151 Addition of a tube of constant curvature, requiring the edge to be a segment of a circle

12.07 PROTOTYPING

Aiming at validating the system's claim of versatility and testing the assumption of zero-material thickness not significantly affecting the theoretical fitting of parts, three prototypes were built: one of the basic system, one with a strip flange (Figure 152) and one with a tubular edge (Figure 153). Furthermore, also practical experience was gained on the relative positioning of parts, the order of positioning and the need and nature of aids during positioning, as well as which data has to be prepared in the engineering phase to facilitate accurate production. Once completed, the ribs were assembled, then measured in 3D and compared to the 3D model. This showed a high dimensional accuracy, proving that the structure is suitable for construction.

Conclusions

Originating from the desire to freely shape reticulated structures, the challenge posed by materialising twisting structural members within this network is to be solved. If in addition to twisting, the members need to follow a curved building envelope, the members should also curve. As this combination is still rare in building structures, the most appropriate precedent was found elsewhere, in tracks of rollercoasters. Aiming at enlarging the formal possibilities of structural design, the Delta Rib structural system has been proposed. It combines unprecedented formal freedom with the ability to vary the elements' mechanical properties to the local needs of structural capacity. In the development of the system production was anticipated such that the system can be built with existing manufacturing technologies.

Nearly a decade after its conception, and a world economic downturn during that period, the architectural scene's focus has shifted to increased sustainable performance and the interest in the further development of the Delta Rib system has faded. Having said that, many technologies for design and construction developed during the Free Form era, have raised the standards, and have acted as enabler for the current architecture and (structural) design practice [Ref. 12.06].

FIG. 152 Prototype 2 during construction.

FIG. 153 Prototype 3 completed.

Acknowledgements
This chapter describes the background, development and prototyping of the Delta Rib structural system. It is one of the structural systems developed as part of the author's doctoral thesis [Ref. 12.05]. Parts of it are based on a paper by the author presented at the 2006 annual symposium of the International Association of Shell and Spatial Structures [Ref. 12.03].

12.08 REFERENCES

REF. 12.01 Boer, S. and Oosterhuis, K. (2004), 'Architectural Parametric Design and Mass Customization, 5th European Conference on Product and Precess Modelling in the Building and Construction Industry - ECPPM 2004, Istanbul (Turkey)

REF. 12.02 Stephan, S., Sánchez-Alvarez, J., and Knebel, K. (2004), 'Reticulated Structures on Free-Form Surfaces', Shell and Spatial Structures from Models to Realization, Montpellier (France): International Assocation of Shell and Spatial Structures (IASS)

REF. 12.03 Veltkamp, M., (2006), 'Delta Ribs: parametrically defined structural members that allow curving and twisting', New Olympics, new shell and spatial structures, Beijng (China): IASS APCS

REF. 12.04 Veltkamp, M., (2006), 'Steel construction component comprises three steel plates connected to each other to form a trangular rib in cross-section, each provided separately with predetermined simple curvature', Patent NL 2000191, 23rd of Augsut 2006

REF. 12.05 Veltkamp, M., 'Free Form Structural Design, Schemes, Systems & Prototypes of Structures for Irregular Shaped Buildings', Research in Architectural Egnineering Series, Imprint: Delft University Press

REF. 12.06 Veltkamp, M., (2015), 'The end of Free-Form Design, love live Free-Form Design!', Future Vision, Amsterdam (the Neterhlands): International Assocation of Shell and Spatial Structutes (IASS)

13 RECOMMENDATIONS AND CLOSING COMMENTS

There are several lessons to be drawn from the case studies concerning the management of complex liquid design & engineering. These are presented under the following headings; process, products and people.

13.01 PROCESS

1 Realizing a free form design must be approached as a collaborative process of design, engineering, production and realisation. The experimental character of this process has to be recognized, costed appropriately, and dealt with as a management challenge, in the sense that the process needs to be designed and then managed. Coordination and integration of all contributors to the total engineering of the building is essential to the successful realisation of free form designs.

2 Production activities are organized on the basis of theoretical drawings of a perfect engineering project, perfectly coordinated and perfectly integrated with the other sub-contractors on the site. Pre-checks to establish a perfect fit and exchange of information as part of collaborative engineering is an essential requirement.

3 Detailing of elements and components will have to allow for accurate 3D-measuring. Click points to be positioned accurately as the reference points both in the engineering as well as in the site surveys. Product 3D-site surveys must be continuously connected to the computer in the 3D mother model so that frequent checks of theoretical and actual click

points can be compared. The site (geotechnical) surveyor is an indispensable service to the main contractor.

4 The architect has a choice between two forms of collaboration:
- Hierarchic: develop the design with the advisors, tender and have the design further developed by the engineers of the contractors, or
- Building team: by composing a team of advisors and engineering co-makers that develops the design and complete engineering of the building, after which the final tendering and realization takes place.

13.02 PRODUCT

1 The architect has three choices for the engineering:
- Only to produce the design concept and the presentation drawings;
- Produce the conceptual design, presentation drawings and the initial 3D-model;
- Produce the conceptual design, the presentation drawings, the 3D-CAD mother model and coordinate the integration of all engineering contributions from the co-makers.

2 The coordination of the engineering of the 3D CAD mother model has to be paid for, either directly through the client's fee or indirectly via coordination costs applied by each partner. The free form architect should emphasise this at the presentation of the design. Failure to discuss costs openly and agree an appropriate budget will have implications for the effective realisation of free form designs and the investment costs of the building;

3 Liquid design buildings are currently more expensive in their engineering than orthogonal buildings because of the high variability in shape of the production elements, characterized as industrial products in lots of one. With the increase of CAD CAM production prices are expected to decrease. The total costs of design & engineering of all parties of a blob design will amount to 20-40% of the total building costs (incl. fee of architects, advisers and co-engineers);

4 Ever sophisticated computer hardware and software has not just resulted in more standardized and more economical preparation and building processes, but also in more complex and creative buildings.

13.03 PEOPLE

1 Trust between the different parties is essential. If trust does not exist with the project it will be difficult to realise collaborative engineering, resulting in contra-engineering;

2 Co-engineers need to incorporate excellent engineering departments that are able to dimension, detail and effectively communicate their experience with buildings in complex geometries. This needs to be done via a common 3D mother system;

3 It is anticipated that with the development of knowledge of blob designs a new breed of blob 'cluster' contractors will emerge, taking over the co-ordination and integration of complete building parts under the umbrella of a main contractor;

4 Failure to appreciate the complexity of blob designs will have consequences for the project partners. This observation relates to all partners, from client and cost advisors, to architects and engineers, to main and specialist sub-contractors. The obvious threat to clients is poor cost advice and hence buildings that are more expensive than anticipated or buildings that have to be compromised to realise a poor cost estimate. Contractors and sub-contractors also have a lot to lose if people, process and product aspects are underestimated. The producing parties will pay these projects out of their own pockets, hence the nickname 'fluid design nightmares' amongst producers.

13.04 CLOSING COMMENTS

The new generation of liquid design buildings, with their computer designed arbitrary and non-rectilinear form, are mainly generated from the sculptural ideas of their architects. These buildings can be designed and realised because of the increased accuracy in complex 3D geometries of computer hardware and software. Design & engineering is the core of the operation and the design decision-making process is an extremely important aspect of these pioneering projects. Complex issues can be dealt with by an analytical engineering approach. In this sense there is not a problem that cannot be solved (assuming the budget allows it), although the most advanced technology needs to be developed even further in order to meet the new geometrical demands.

The challenge of realising liquid designs relates more to the managerial frames in which they are conceived and realised. Free form buildings require considerable investment in time and effort and demand collaborative design and engineering approaches. Communication, collaboration and trust are essential elements in the management of these creative and demanding projects. In the design phase the concept of the buildings technical composition would be developed simultaneously with the architectural concept. Both in the design & engineering phase as well as in the productions & realisation phase an extremely high degree of collaboration between all partners is required to ensure a successful outcome for all. This implies that the design of the process and the assembly of the people is as important as the technological aspects, a point consistently experienced in the case studies described above. So in the drive to make free form architecture more attractive to clients it will be necessary for architects, engineers and specialist contractors to improve their coordination and managerial skills to match the software packages and sophisticated engineering that can be deployed.

13.05 REFERENCES

REF. 13.01 Berkhout, G. (2000), The Dynamic Role of Knowledge in Innovation, Delft University Press, Delft

REF. 13.02 Cook, P., (1999), Archigram, Revised Edition, Princeton Architectural Press New York

REF. 13.03 Eekhout, M., (1989), Architecture in Space Structures, 010 Publishers, Rotterdam

REF. 13.04 Eekhout, M., (1992), Between Tradition and Technology, Publicatiebureau Bouwkunde, Delft

REF. 13.05 Eekhout, M., (1997), POPO, Practical Methodology of Component Design & Product Development for Architecture, Delft University (Procesorganisatie voor productontwikkeling IOS Pubsilshers, 2008)

REF. 13.06 Gomez, J., (1996), La Sagrada Familia: De Gaudi al Cad, (The Sagrada Familia: from Gaudi to CAD), Edicions UPC, Universitat Politecnica de Catalunya Barcelona

REF. 13.07 Nijsse, R., (2003), Glass in Structures, Birkåuser, Basel

REF. 13.08 Rice, P., & Dutton, H., (1995), Structural Glass, E&FN Spon, London

REF. 13.09 Tombesi, P., (2002) Involving the industry: the use of 'request for proposal'packages at Frank O. Gehry and associates. in Gray, C., & Prins, M., (eds.) Value Through Design, CIB publication number 280, CIB, Rotterdam pp. 171-179

REF. 13.10 Zwarts, M., Ibelings, H. Jansma, Mensink, J., Rijnboutt, K., & 't Hart, R., (2003) Zwarts & Jansma Architecten 52 ° 21"N 04 ° 55'51", (Zwarts & Jansma Architects 1990-2003), E, NAI uitgevers, Rotterdam

14 EPILOGUE

After more than a decade full of Delft experiments on 'Free Form Designs' and 'Blob Technology' in the chair of Product Development at the TU Delft an evaluation is appropriate. This brings an overview with a number of issues:

- Experimenting with design proposals in practice will enhance the interest in new fields of technology like Free Form Designs, although driven by optimism and naivety a number of design proposals were not properly dealt with in practice. Those designs were immature, experience was lacking in all heads (designers, engineers, producers and installers) and brought disappointment as a result;

- The early years are marked with costly technical failures and financial sacrifices;

- They led to the Delft 'Blob' Research Program as a scout for future practical applications;

- Experimenting and building of small scale prototyping was very helpful in engineering new Free Form techniques such as explosion deformation of aluminum panels, hot bent glass panels and vacuum sucked injection molding;

- The upgrading of standardized 3D computer programs stimulated designing and engineering up to a higher level: Maya, Rhino, 3D Studio Max, for designers and Autocad/ Inventor for engineers, and others for geometrical surveyors;

- The use of 3D-CAD models is an absolute necessity for the design and the engineering phase. Before the building industry started BIM (Building Information Model) out of management reasons, Free Form Technology developed it as an indispensable tool for fixing the geometry of the entire technical artifact. The building as an artifact consists of its components and elements, and because of reasons of accurate and consistent technical coordination and integration in the 3D Mother Model the BIM model is an unavoidable co-ordination and integration tool;

- Only in some cases the project was preluded by an appropriate prototyping. Both clients, designers and producers benefit from this prototyping. In the early days of a new technology a close collaboration between all parties is necessary, with mutual trust and confidence as a base;

- With the wise phasing of a project introducing a prototype phase before the final engineering phase (like the sandwich roofs for the Rabin Center in Tel Aviv), a balanced approach of an experiment has been achieved;

- In the Mediateque of Pau (France) the municipality wanted to go straight ahead into a European straightforward 'design & build' tender, which turned the tender process based on a Free Form Design (on a scale never done before) with (CRE) Carbon fiber Reinforced Epoxy sandwich roofs (materials never used in architecture before) a disaster. A prototype phasing would have resulted in more knowledge, insight and trustworthy financial calculation data;

- In the meantime architects dream on and many international design competition of public buildings display a very free geometrical form of architecture;

- The building industry is not yet ready for Free Form Design buildings on a larger scale, although the current credit crisis has toned down many initiatives of clients. At this moment in time many producing and contracting building companies are just trying to survive;

- The three basic issues:
  - the building as a technical artifact;
  - the composing components;
  - the total 3D design, engineering & building model deserve further research & development.

So that Free Form Technology will be more mature when the crisis and the eventually following recession will be over and the lust for Free Form Design buildings will increase again.

Prof.dr. Mick Eekhout

Professor at the Chair of Product Development 1991-2015
www.mickeekhout.nl
a.c.j.m.eekhout@tudelft.nl

Director of Octatube Delft
m.eekhout@octatube.nl