TUBULAR STRUCTURES IN ARCHITECTURE

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For structural engineers tubular structures are most interesting for buildings with larger spans. For architects other tendencies in the design of tubular structures of buildings are valid which have an influence on a much smaller scale, more intense, often more complex than just large spans. From the 1970-ies onwards high tech architectural caught much attention. From 1995 onwards, accelerated by the intense use of the computer, attention came also on deviating geometrical forms of buildings, the fluent form buildings and the free form buildings. ‘Fluent’ forms of buildings have geometries which can be derived by mathematical formulas and hence are more or less communicable. Free forms are free forms and literally cannot be generated by mathematical forms. The form of these buildings has to be established by the architect and other parties just have to follow. Yet the future of tubular structures is only colored by these pilot projects. The majority of applications is still quite functional and straightforward.

Keywords: Architecture, tubular structures, free forms, high-tech.

1 Introduction

Since half a century tubular structures are popular in architecture. Originally they were seen as substitutes for classical open steel profiles. But the circular and square cross sections had better advantages over open profiles. Tubes were developed gradually and finally exploited to achieve results that were never dreamt of with conventional steel structures. Material efficiency of the cross section led to open profiles, extremely good for bending. Tubes are better in compression. But tubes also have an esthetical appearance which lifts them above open profiles. They are not angular, but more fluent. In general they give a more smooth appearance in contrast with the more robust open profiles. In designing tubular connections they can be chosen as being abruptly in case of many tubes connecting to one point or being smoothly when forces are visually flowing from one tube into other tubes.

Figure 1. Abrupt connection of tubes

Figure 2. Smooth connection of tubes

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The development of tubular structures, load bearing structures, in general for larger spans, not only has been guided by its pure function of load capacity by structural engineers, but also has increasingly been influenced by architectural engineers with a bit more design considerations involved.

2 Product development of tubular structures

The time of standard products seems over. In the trio of standard products, system products and special products in product development, the system products like space frame structures are also almost past. Architects want to design their own structures with a remarkable project characteristic. From the experience with system products we know the base of system products are half-products like steel tubes and pipes, which get a free form production treatment, often maltreatment: cornering, bending and curving, all to transform simple straightforward steel tubes into ingenious tubular components, each with their own form and connections, but at a cost. We can apparently afford this as we are living in quite a luxurious world.

Despite this reasoning in general in the last decade regular geometric structures were favourite and still make up the vast majority of buildings nowadays. It is the rational structural design towards minimal material use, combined repetition in production and assembly that makes economic structures. Frei Otto was the pioneer of minimal structures, leading to his membrane and cable net structures of the 60-ies and 70-ies in complete separation of tensile forces (in membranes and cables) and compression forces (in masts and foundations).

Figure 3. Olympic Stadium Munich, Frei OttoMajor Headings

Extreme separations of forces lead to heavy foundation anchorings, out of sight. which do not directly follow the laws of minimal material use by larger bending moments than usual. In effect the minimal material use has been lost ever since the ‘Bird’s nest’ of Beijing, China (2008) which consumed 8 times the amount of steel compared to a regular stadium of the same size.

Figure 4. National Stadium ‘Bird’s nest’ Beijing

However economic structures do not make a winner at competitions when the jury knows that much more geometries are possible. Architects get bored by predictable regular geometries. They want to design and not only obey the laws of regularity in geometry. They want to win a design competition by astonishing the jury or the client. The omnipotent abilities of computer rendering and later structural analysis by computer make tubular structures very suitable for structural manipulations. Irregularity, because of architectonic reasons became more experimental for architects to win design competitions with designs that amaze the jury and later on the world. Designs of new stadiums prove this.

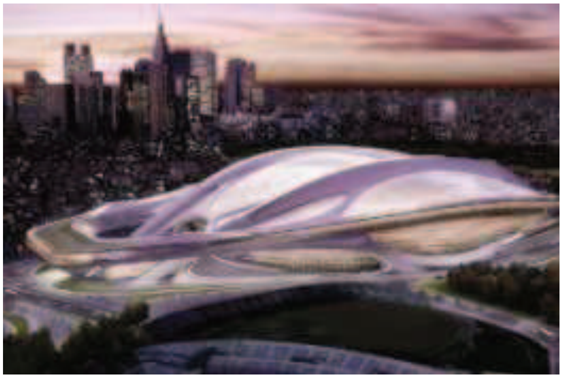

Figure 5. Design Competition for 2020 Olympics: National Stadium Tokyo, Zaha Hadid

3 High-Tech structures

In 1997 the CIDECT / TU Delft book 'Tubular Structures in Architecture' was published in 5 languages and 25.000 copies were sold over the world. In between the distinguished company of structural engineers an architect, an engineering architect or an architectural engineer always has a different view. Which resulted in this book 'Tubular Structures in Architecture' mainly explaining the possibilities, reasoning and realized examples of 'High-Tech' Architecture. Actually, high-tech architecture was introduced for the world in the Beaubourg Centre as an explosion "to change fashion in architecture" as the late Ted Happold, collaborating engineer of Renzo Piano, would say in 1986 in Sydney.

Figure 6. Centre Pompidou, Paris

High-tech architecture became popular in the world after the Pompidou Centre in 1978. As it were it turned the normal straightforward reasoning of structural engineers upside down. Why design an obvious and simple structure, when you can also design an astonishing or even an exciting structure? Nowadays, more than 20 years after the first issue of the book, a generation alter, one could say that the book was written in the middle of the high-tech era. Structures of buildings, load bearing structures had always been important in the design of buildings, but they were never much concern of architects. But showing them, showing the structural act made structural design exciting for a whole generation of architects. Designing according to the bending moment lines in a structure had its own appeal for architects. It made structures even more understandable and prominent for the observer and for the user of buildings. In many structural high-tech designs the separation of tensile forces and compression forces play a visual role, sometimes even exaggerated as a show-off.

The book was written, however, on realised hand-designed structures, with hand-engineered details and shop drawings. Sometimes it was a wonder that, without the exact surveying apparatus, these prefabricated structures fitted in reality on the mm. The eleven roof segments of the 50 m space frame for the Aquadome in Bremen were installed, but would the closing segment number 12 fit? It actually did, the open space for segment nr 12 was 3 mm too wide, easy to be fitted in with washers rings. It was exciting like a rocket Launch!

Figure 7/8. Aquadrome Bremen

High-tech structures often were products of a deliberate collaboration between the architect and the structural designers in one project, a collaboration more intense than before. Architects understood high-tech structures. Kanzai Airport designed by architect Renzo Piano and structural engineer Peter Rice mark the moment in time in a flow over towards complex geometry design. The design followed a complicated geometrical form with a large radius for the roof form. Producers who had underestimated the complexity of these tubular design structures could easily suffer gigantic losses on these early free form architectural projects.

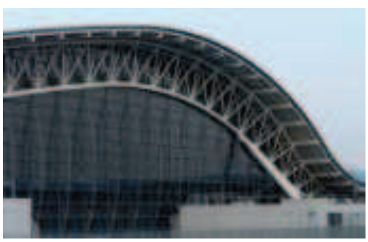

Figure 9. Kanzai Airport, Osaka

4 Sculptural designs and free form structures

Only 15 years later, in 2011, the second, the extended edition of Tubular Structures in Architecture was written and published. Drawing tables already had been removed from the architect's offices. The influence of the computer in architectural offices was amazing. The computer was seen initially as a substitute for boring or complicated hand-made designing and engineering. From the mid 1990-ies the use of computer programs in the architect's office gave unexpected and exciting results. After confirmation of the flawless geometrical computation capacity of computer programs more complicated designs enabled more complex geometries to be realised. The introduction of the computer evoked more complex designs in tubular structures than were possible to be realised ever.

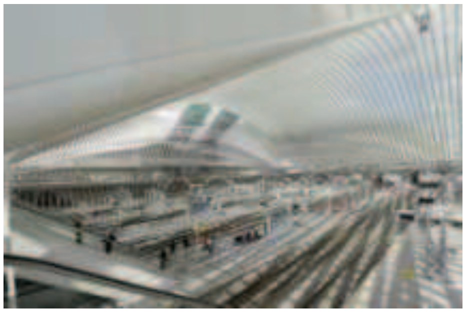

Figure 10. A complex tubular structure; Guillemins Luik, Santiago Calatrava

4.1 *The Guggenheim museum in Bilbao was the start of free form architecture*

The transition in architectural geometry was dramatically pointed in history by the Guggenheim Museum designed by Frank O'Gehry, and realised in 1997. It was the flagship of free-form architecture. I remember for the first time I saw it, when giving a lecture in Bilbao on the issue of 'Tubular Structures in Architecture', I had to adapt my carousel slides. The museum had come as a satellite from outer space, landed in Bilbao and changed the outlook of the entire city. A building under construction for a shopping centre a bit further down the river all of a sudden looked helplessly old-fashioned, almost 1960-ies. So only one building changed the outlook and the future of an entire city. A former industrial harbor city all of a sudden became the world place to be for tourists. Bilbao is Guggenheim and Guggenheim is Bilbao.

Figure 11. Guggenheim Bilbao by Frank Gehry, approven appearance

But the technology employed for this building was outdated. Photographs of the construction work were hardly published. Open profiles with large connection plates and all members welded on the site, so that they would fit. It was building a new design with old-fashioned ingredients. May be Gehry had been shocked by the performance on site so that in a next project he became more fierce on his explicit design engineering.

Figure 12. Load bearing structure of Guggenheim Bilbao during construction phase

4.2 *Risky design developments as moonshots*

Bold architects even went so far to design even ‘free-form’ structures that were impossible to be built before computerisation of the architectural designs. But too early adopting and too eager architects saw mishappenings. Designs by architects without knowledge of adapted execution in production and on site either caused projects to be cancelled, architects on the blacklist of clients, unfortunate production parties to go bankruptand almost bankruptcy of Europe’s most famous curtain wall company Gartner, taken over by Permasteelisa.

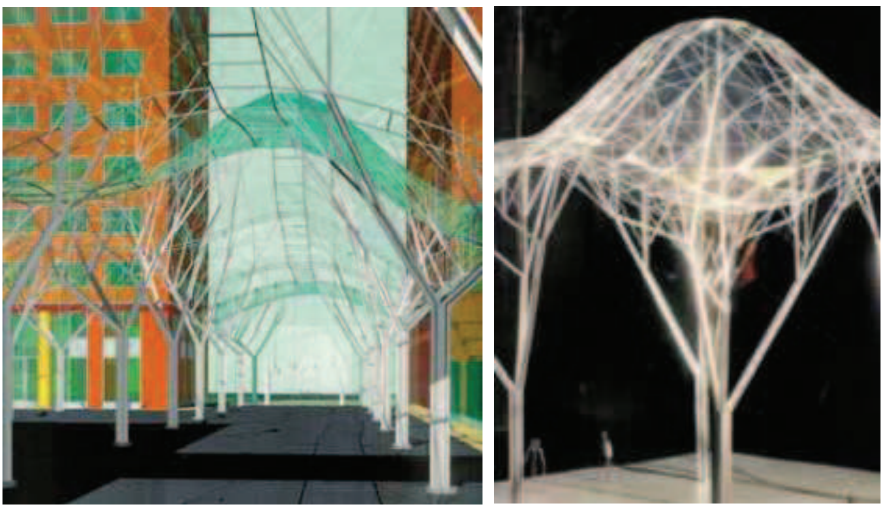

Figure 13/14. Structural proposal Wilhelminapier, Zwarts & Jansma

We say now: these architects were light years ahead of their time. Sometimes they were much too early and underestimated the capacities of the production industry to execute their designs without any prior knowledge gained from previous projects as there were no prior projects.

Figure 15. Deutsche Genossenschaft Bank Berlin, Frank Gehry

For production companies these 'moonshots', which are very complicated projects with an aim, but without appropriate knowledge and no prior experience, can be killing and leading to bankruptcy. Usually producers say: the architect is praised and the churchyard is full of 'naïve losers' and other disillusioned contractors. So free form architecture and the shortage of experience and proper production efficiencies also led to a number of economic failures.

Figure 16/17. Roofs of the Rabin Center, Tel Aviv, a personal 'moonshot' project, see figure 25.

Gradually, after a number of abortive projects, and later of a number of hardly successful projects, after publications on the required and more or less (economically) successful free form technology, more projects were realised. As always design-eager architects and wealthy clients were praised. It lead to understanding and further development of the required free form technology. The road to success is paved with many 'moonshot' gravestones of producers.

After many free form structures one could notice that the adage of light weight structural design as in the 'minimal material' era of Frei Otto is forgotten and has been exchanged by heavy and moment-stiff structures, see the 'form driven' designs of Frank Gehry.

Figure 18/19. Louis Vuitton Museum Paris, Frank Gehry

4.3 *Prototyping to get acquainted with new technologies*

An alternative for the initial absence of appropriate knowledge in this upcoming new field of expertise was to make use of material prototypes to be built during the design process or engineering process. Prototypes designed and engineered by the architect and structural engineer would reveal to the offices many uncertainties and secrets that cannot be seen from computer models, not even the most advanced types. Small details are worthwhile to be made in real materials, manipulated in the hand of the designers to get accustomed with real material, real sizes and weight of material details. There are always material flaws. Large scale prototypes cost extra money, of course. Dutch clients do not want at all to invest in such prototypes, as they see it as superfluous energy and investment. In America and in Asia, however, we have experienced that making prototypes is often more common practice.

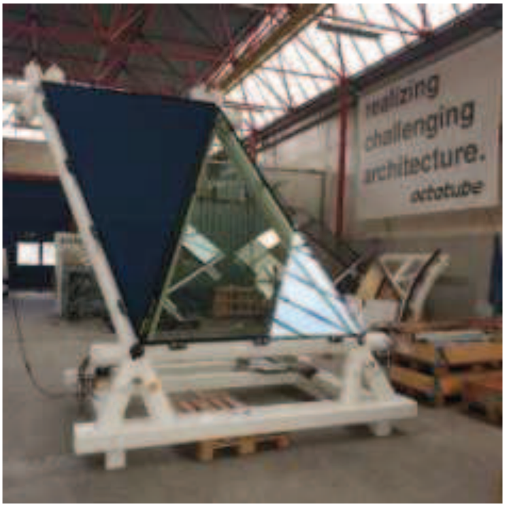

Figure 20. Prototype Afas Dome at Octatube

Figure 21. Testing of mock-p for earthquake resistant Quattro SR in Tokyo

From prototypes not only one party can learn, but all involved design team partners can gain. And if performed before a tender is issued, all tendering parties could draw their lesson which prevents also ‘wild west tendering’. In many projects the client can prevent loosing much money as this prototype is seen as an efficiency maker for the entire process.

Figure 22. Tubular space frame in the roof of Raffles City, Singapore

In other cases the internal fights in a building design development and engineering team could be hastened when previous experience is visual. Also a question of time, to prevent a loss of time.

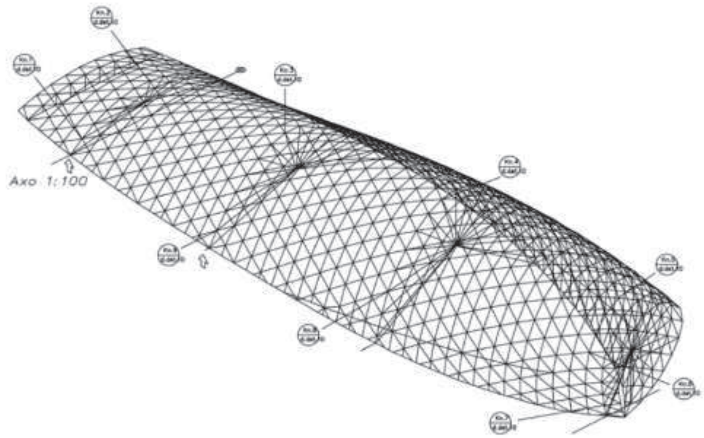

Figure 23. Octatube's alternative design of the Deutsche Genossenschaft Bank Berlin

4.3 *Frontrunners*

Architects who were working enthusiastically at the forefront of new development of free form design were only retarded by the production and construction industry who had no idea how to make free form constructions with elements and components that were deviating from producing simple tubes and nodes. Architects and engineers did not collaborate with producers to develop a free form production technology. They expected that throwing over the wall as an invitation for tender would automatically generate success. Well at first it harvested impossible prices and generated much misunderstanding.

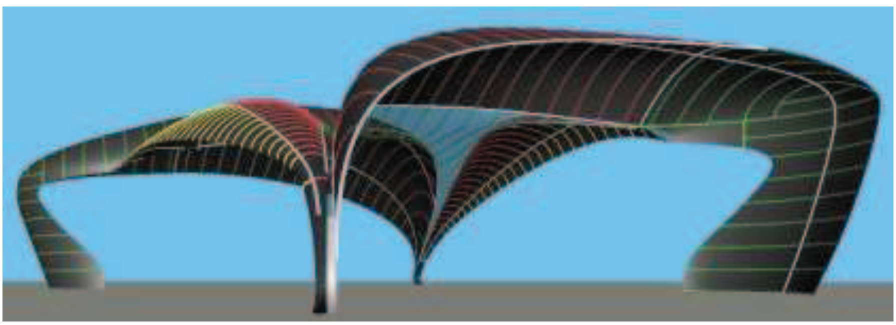

Figure 24. Elevation of the 45 x 75 m large Mediatheque's roof structure of Zaha Hadid by Octatube

They said: "The industry could not cope", et cetera. Dreaming on computer aided manipulative geometries went far beyond the imaginations and usual and experienced capacities of the producing parties. They could not diminish the many risks involved.

4.3 *Self-overestimation or 'moonshot' thinking?*

In 1962, President John F. Kennedy speeched the message: "We choose to go to the moon in this decade", that was the beginning of the ambition of an entire nation to go to the moon. We could say that JFK did not set that goal by knowing how we could achieve it or by promising it would be easy, he simply said that we were going to accomplish something incredible, setting the timeframe and inspiring toward action. The money would come later.

In case of the Rabin project (Fig. 16/17) my company Octatube and myself had to overcome a 'moonshot' with as much of eight innovations packed in one project:

- Glass fibre reinforced polyester
- Free form architecture;
- New computer programming;
- All elements and components integrated in big BIM model
- Large smooth surfaces required
- Innovative production out of our sight in a specialist factory;
- Hostile attitude from the Israeli approving officials
- Assembly out of sight 5000 km from the office

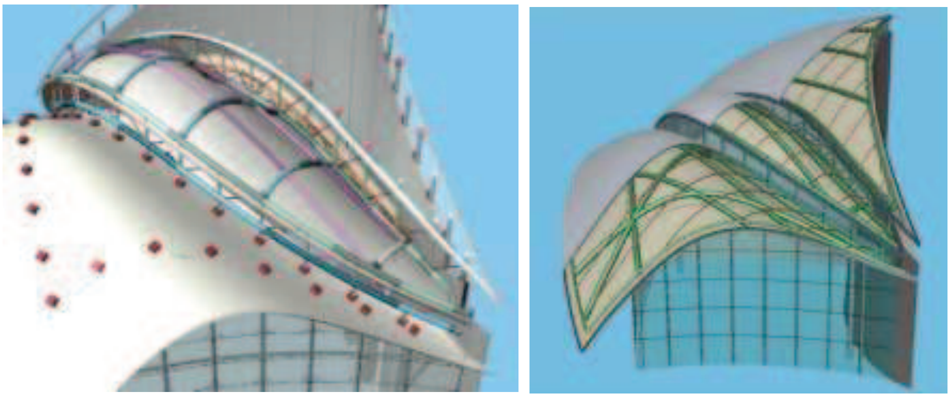

Figure 25. 'Moonshot'-project Rabin Centre, eight innovations in one project

This obviously led to an almost unmanageable technical innovative project. 'Moonshot thinking' is derived from NASA working with endless governmental budgets, unlike the discrete budgets in projects or companies. But project budgets are restricted and so are the company's limits.

With only a few projects per year in any country the eagerness amongst producers to adapt their production capacities in their own companies was not overwhelming. But for large pilot projects, mostly prominent projects, money was available to adapt the production capacities by introducing computer aided manufacturing, by introducing associated assembly methods with a main focus on geometrical surveying. Architects like Frank O'Gehry had obviously learned from Guggenheim and dictated in this millennium their own specifications in the designed compulsory form of free form components. Gehry specifically requests his buildings to be built as he has designed and engineered, no alternatives possible (Fig. 18/19). Manipulating managers almost caused the best European curtain wall company, Gartner, to go bankrupt on that project.

4.4 *Producers or specialist contractors?*

Other manufacturers developed their own vocabulary to have an building technical answer on the free form architectural designs. Usually these designs are quite large and within the development of the project there is space and money available to develop a new production vocabulary for each new free form project. With many experiences in the Octatube office as illustrated in this publication the technical engineering of a free form architectural design often follows a particular project characteristic.

Figure 26. Design Proposal Capital C, Diamond Beurs Amsterdam

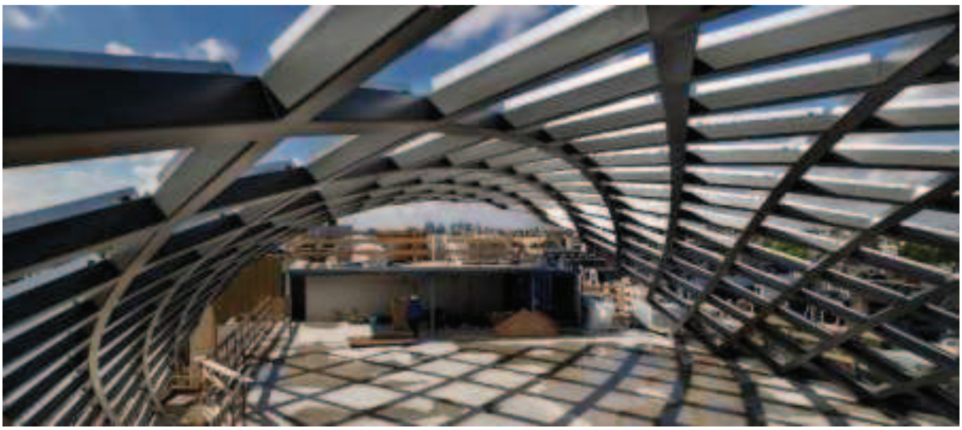

Figure 27. Construction photograph Rokin cylindrical roof, Amsterdam

All architectural designs are different. The architect want to employ ‘the first of the block effect’: the first car lover drives a pink Cadillac. The second one never will buy a pink Cadillac as he does not want to copy the forerunner. An architect never wants to be seen as an imitator or an adaptor of another architect with a previous project, but always strives to be purely original. Which just does not lead to system engineering and production. It leads to ‘Industrialisation in lots of one’. Most of the experience from earlier designs cannot be directly or literally used in a next project. What remains are the willingness to perform free form technology, to exploit the process experiences from earlier projects, the free form engineering attitude and of course as a means to the goal the computer programs inter-relating between architectural design, component engineering, production machining and the geometrical surveying of the components in the expected positions on site. But attitude and experience are first.

My own professional part as an architect in the world of structural designers and structural engineers led me to develop a new vocabulary in space frame structures, all of tubular components, and later of glass structures by undertaking many successive ‘design & build’ projects.

Rather smaller projects at first with clear or restricted risks, an incremental approach. 'Step by step' as Piano once wrote. Never throw as an designing engineer an impossible design over the fence and expect that it would work. Misinformation from the designing parties, misunderstanding, misinterpretation and lack of motivation from the side of producers do not lead to successful answers by producers in tender processes. When you, as a design engineer, do not know how your design has to be made, don't expect others to take up that risk either.

5 Complex Tech-Architecture

- Tubular designs are visual designs pleasing for the eye.
- Tubular structures are easy to be manipulated in the design phase: bent or curved;
- The geometry of tubular steel structures is increasing in complexity due to design manipulations with the aid of computer programs;
- Tubular structures become integrated part of the building envelope;
- Complex detailing beyond the structural function is required around tubular structures.

More in detail, architects have the tendency to make the 'basic' tubular structures more complex by outside and inside cladding and glazing, by mixing tubular structures with other structural materials like glass, by adding more functions like sound absorption and by designing project-typical structures

Perhaps the best drive for continuous quest for disruptive innovations in tubular structures results from curiousness, creativity, persistence, a bit naivety, a positive spirit and belief in ambitions and of course, the joy in making new things that last.

6 Examples of projects from regular to irregular geometry

6.1 *Air Traffic Control Leader bridge, Schiphol Airport NL*

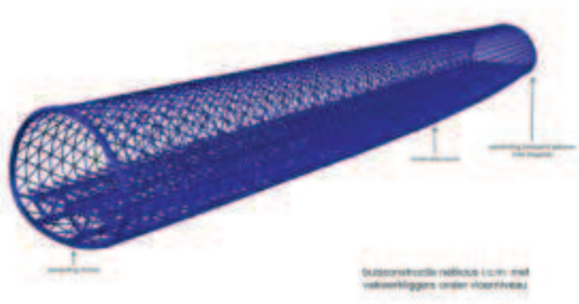

Figure 28-31. Air Traffic Control Leader bridge

Air Traffic Control Leader bridge at Schiphol Airport, a pedestrian bridge of 50 m span between two buildings at Schiphol Airport, Amsterdam, made of circular or square hollow sections in a regular structural system. The original design showed a sigar-shaped form with a wider cross section in the middle of the span and a smaller cross section at both connecting sides. But this cigar-form was substituted by a straight elliptical form due to cost reasons. It saved approximately 30% on the total budget tubular structures and sandwich claddings and glazing panels together. Architect: Ector Hoogstad Architecten

6.2. AFAS Dome, Leusden NL

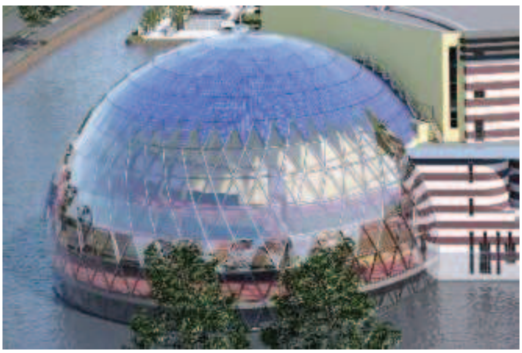

Figure 32/33. AFAS Dome, Leusden, NL

AFAS Dome, Leusden, NL, as a regular network dome made in CHS with welded connections, and highly sophisticated glass cladding, with internal cabling of lighting, computing, installations. The dome is under construction at the moment of writing. The model shows that the connections are made as rigid bolted connections with 4 internal bolts. In the centre of the CHS tubes enough space for electrical cables. Architect: Steef van der Velt in collaboration with Just Architects.

6.3. Friesland Bank Dome, Leeuwarden NL

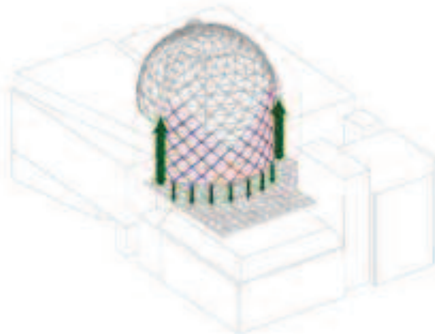

Figure 34/35. Friesland Bank Dome

Friesland Bank Dome, Leeuwarden, the Netherlands. A dome structure in a regular geometry, but suspended form 3 arches, as the foundation possibilities only allowed 3 anchoring foundation points between existing buildings. The dome structure has also been loaded by a large flat roof on one side, at the side of the open atrium. Architect Aad van Tilburg, Rotterdam / Harmen Grunstra, Bolsward.

6.4 Hudson Bay, Amsterdam NL

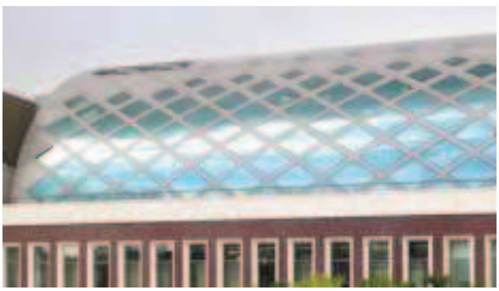

Figure 36/37/38. Hudson Bay

Hudson Bay Amsterdam, has a top floor restaurant, with a beautiful sight overlooking the centre of Amsterdam. The form of the tubular structure concerns a regular cylindrical shape made of RHS which have a slight twist incorporated in the connections to amaze the world with a diagonal geometry instead of the usual orthogonal geometry. It gives the indoor space a 'swing'. Architect: Rijnboutt.

6.5. The Southgate Canopy, Delft NL

Figure 39. Southgate Canopy

The Southgate canopy in Delft has been made in a waving system of circular hollow sections, CHS, specifically to show the possibilities of cold warping of laminated glass made with flat and orthogonal glass panels. Architect: Mick Eekhout

6.6. London Business School, London

Figure 40/41. London Business School

London Business School, London has two intermediate glazed spaces with specially made triangular hollow sections in an irregular composition. The triangular hollow sections leave no shadow at their lower side. They leave attention for the three existing Victorian buildings which they connect. Architect: Sheppard Robson.

6.7. Glass House, Malmö


Figure 42/43. Glass House

The Glass House of Malmö has a smooth form made entirely in flat glass panels, supported by a waving structure of CHS tubes in an elliptical form and a connecting rib at the top. Design Monica Gora and Ian Liddell / Happold

6.8. Van Gogh Museum Entrance Hall, Amsterdam



Figure 44/45/46. Van Gogh Museum

The Van Gogh Museum Entrance Hall in Amsterdam has only a basic structure consisting of two free formed CHS on 7 CHS columns with steel shoes to fit in the laminated glass fins which were produced in China. So the shoes had to be provided with a very high accuracy of only a few millimetres, which is seldom in free form. The two tubes are 3D bent. Architect: Hans van Heeswijk

6.9. Diamond Exchange Building, Amsterdam NL

Figure 47/48. Diamond Exchange Building

The Diamond Exchange Building in Amsterdam has been provided with a free formed grid as a topping up shell roof made of rectangular hollow sections. The system was made in the form of a square single layered grid of which each member and each node was different because of the free form geometry. The shell has been made in the form of separate ladders, welded on an accurate mould, with singular members in-between, to be bolted on site. Architect: Zwarts & Jansma.

6.10 Atrium Shell, The Hague NL

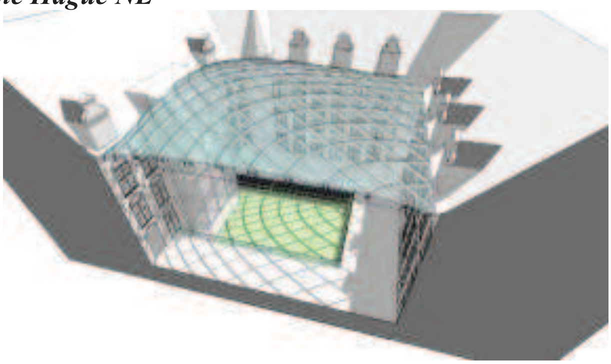

Figure 49. Atrium Shell

Design perspective of RHS structure for covering a rectangular atrium for Shell International in The Hague . In this lightly cambered proposal the RHS members all have different lengths and connection corners. The production methods of rigidly welded ladders with exact corners XYZ require a high precision and many geometrical surveys during production and assembly.

6.11.Notre Dame, Paris

On April 15, 2019, the roof of the Notre Dame burned off completely, inclusive the central roof tower. The roof construction was entirely built of oak wood, more than 8 centuries old. All over Europe medieval churches have timber roof structures that occasionally ignite after maintenance activities. Insufficient fire prevention measures can be quite expensive on the long run. France will organize an international architectural competition, in which the obvious discussion between tradition and amazing innovations will no doubt be celebrated.

The technical solution, however is simple. The plan of the cathedral is made of modules 7,5 x 15 m, the central module in the crossing is 15 x 15 m. Which makes it ideal for an old fashioned tubular space frame. The roof angle of 55 º leads to a very regular space frame in cross form with 15 m long tubular elements, which can be refined up to a module size of 7,5 x 7,5 m². The advantage is that a three-dimensional space fame has a large rigidity in both directions of the plan and on all of its support points. Many of these support points, the tops of the flying buttresses, have had a high thermal attack during the roof fire and can be supposed to have been bent outward. The nodal points of this space frame can bring the entity of the tops of the load bearing masonry construction at rest, either by fixing, or even by post-bending backward to relieve the extra compressions caused by the fire.

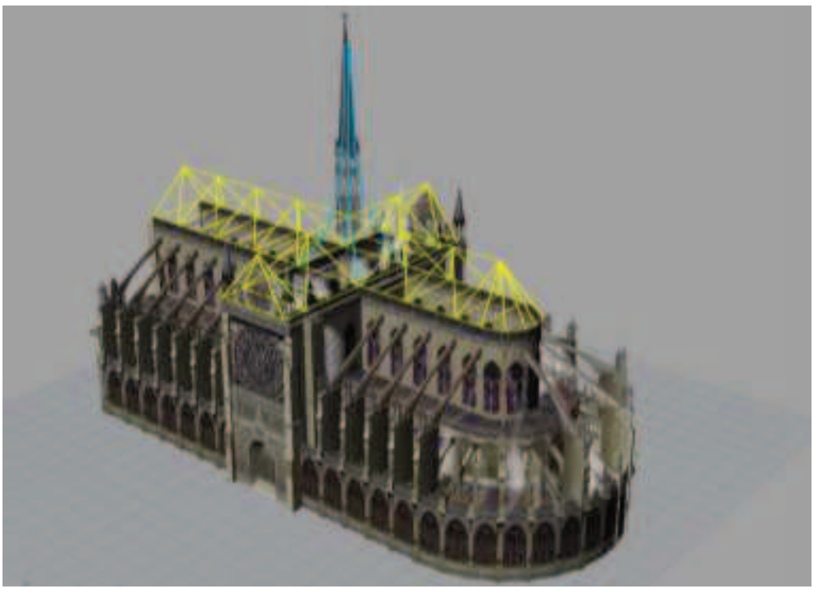

Figure 50. Possible roof structure

The cladding can be made as traditional by led panels on metal purlins or by relatively new materials like glass which gives the possibility to have daylight enter into the central vault, which has been punched through by the collapsing central spire. This central vault could be reconstructed by glass blocks functioning as a brick vault, but now allowing daylight to enter in the cathedral. So tubular structures can contribute in a modest way to the restoration of a famous cultural building.

7. Conclusions for the Architectural Future of Tubular Structures

The architectural future of tubular structures is different from the structural and industrial use. In the domain of structural engineers and tube producers the vision of architects and designers, illustrated by their proposals and realized projects, illustrate the state of the art of the architecture of tubular structures. The multitude of tubular applications is quite straightforward. However, architectural innovative design thinking leads a future qualitative way forward. The era of high tech structures with its rather mechanically steered geometry, is apparently over. The era of 'free form' structures has introduced complexity and complicatedness in geometry. After two decades of trial and error it has been split into 'fluent form' and 'free form' structures. 'Fluent form' has a communicable geometry because of the mathematics behind it, however complex that may be. 'Free form' structures are really sculptural structures which are conceived by the designer as a sculptor, without any mathematics behind it. Many of the complicated structures of Frank Gehry are 'free formed' form random folded paper props, that are 'frozen' from the moment it leaves the table of the handicraft master. They are measured and then put into a strict obeying geometry. No wonder that engineering, producing and realizing parties have to purchase the same computer programs (i.e. Catia) that Gehry Associates use in their design, to assure that the engineered geometry is exactly the designed one, which they can supervise. In following this approach Gehry remains master of the game, all the way through to the opening of the building. But it is a demanding approach for the executing parties. Free form geometries are expensive to realize. In case of the Rabin Center in Tel Aviv architect Moshe Safdi gave a 'free form' model, which had to be adjusted and refined. It was drawn in a 3D-model which could only be handled by one particular engineer. This project followed a similar route of development as Gehry's design & engineering development. 'Fluent form' designs (composed from complex mathematical models), have less problems in the communication. These forms can be mathematically generated by different parties involved in the building team of a project. No wonder that a wise architect sells a competition winning design as a 'free form' design but generates it towards realization as a 'fluent design'. The more repetition, the more economic the structure will be. Buildings with 'industrialization in lots of one', can be made, but at a cost.

In all, architects are very interested in the more sculptural architectural designs than just straightforward designs. Tubular structures have excellent characteristics to be handled as sculptural structures, pleasing for the eye.

Acknowledgments

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