PLENARY SESSION II: TECTONICS IN PRACTICE FROM FRACTURE TO FORM

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The speech describes some practical results of my theories on the correlation between fracture and form. Two of the results are erected in Paris: The Symbolic Globe at the headquarters of UNESCO and la Grande Arche. (The speech was supported by 120 colourslides).

To understand the theories we have to start with some considerations about constructions carrying a weight or a force in the middle of two supports. (Figure 1a.) All beams carry the same force (the same weight) but—the forms (of the beams) being different, the net weights (of the beams) are different too: For a solid beam it is necessary to use 920 kg of steel. For a profiled beam only 465 kg of steel are necessary. If you increase the height of the beam 380 kg of steel are sufficient, and if you choose an ordinary lattice, 140 kg are sufficient. The least massive structure, the minimal construction, need only 43 kg of steel (1/20th of solution No. 1. Almost the principle of a bicycle wheel).

Figure 1b shows a pattern of fracture which is the result of a big force in a plate. Notice that the angle between the yield lines everywhere are 90° and that there is a resemblance between the yield lines and the minimal structure. The geometry of the right angle is necessary to all minimal structures. These orthogonal curves are well known, but the fact which was not known (the fact which is new) is, that to be able to construct a minimal structure you have to use the right angles as known in the geometry of the yield lines.

In 1971 I showed the fundamental correlation, both physical and mathematical, between FRACTURE—FORM and GROWTH. Thanks to this correlation it is now possible to conceive and explain many phenomena where forces appear. A study of fracture lines can reveal the most efficient use of materials: to make structures as solid as possible with the use of a minimum of materials. In other words: to find minimal structures.

Let us stay in the world of minimal structures. Earlier we have examined the connection between structure and fracture. Now it is between structure and growth. Figure 2a shows a minimal construction consisting of logarithmic spirals. We recognize the same lines in the middle of the marguerite. (Figure 2b). The minimal structures are observed in the big universe: An explosion showing that fracture shapes a spiral movement. This is the process that dates from the origin of the universe. Figure 3 shows a project based on minimal structures. Here I have used the spiral principle around each of the eleven supports. Every time two cables meet in the right angle I have placed a light fitting.

And here (Figure 4c) almost a minimal structure: The angles are not all right angles due to their function. It is the

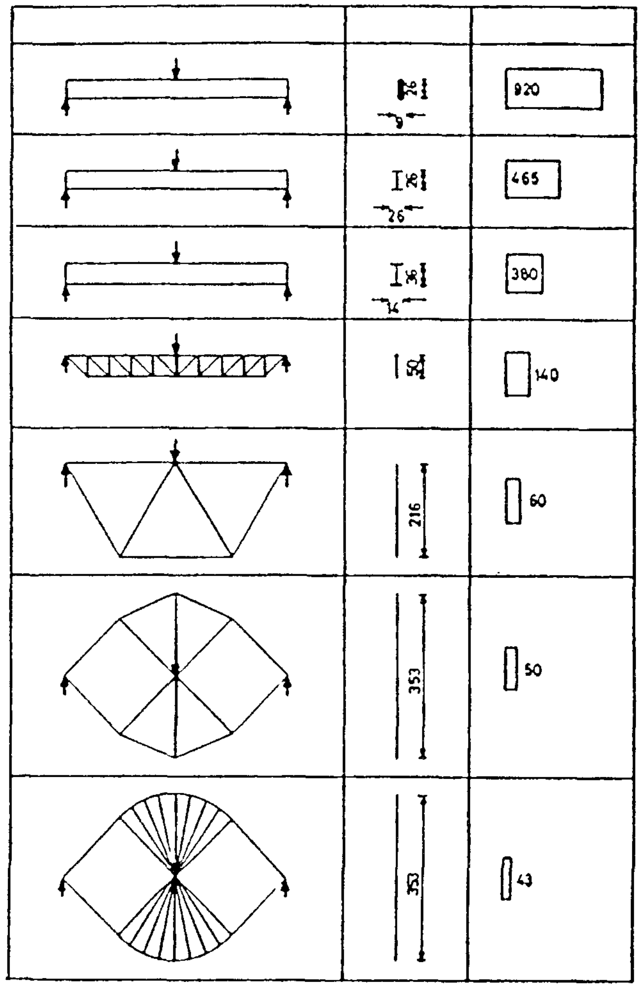
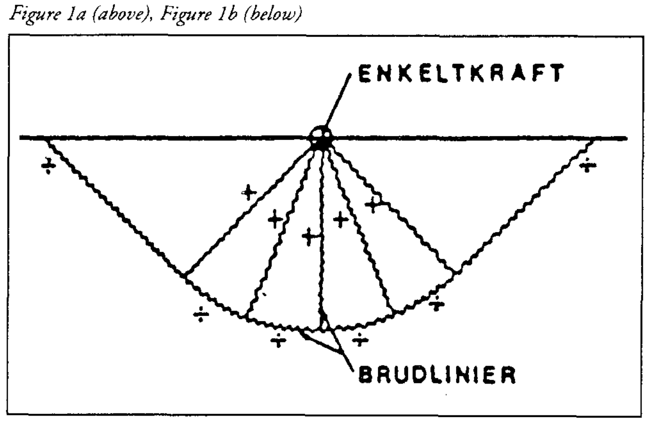
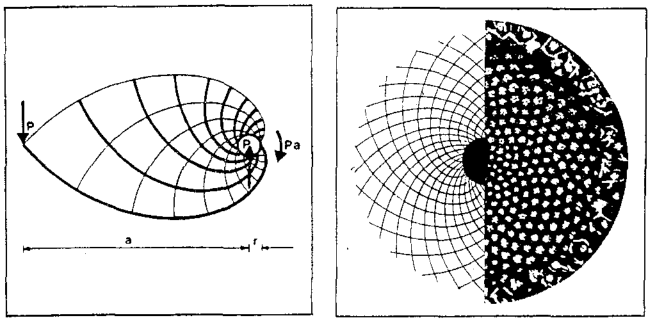
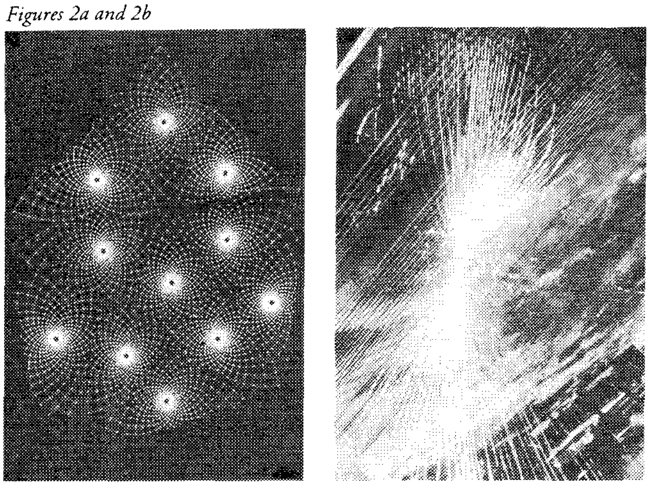


Figure 1a (above), Figure 1b (below)

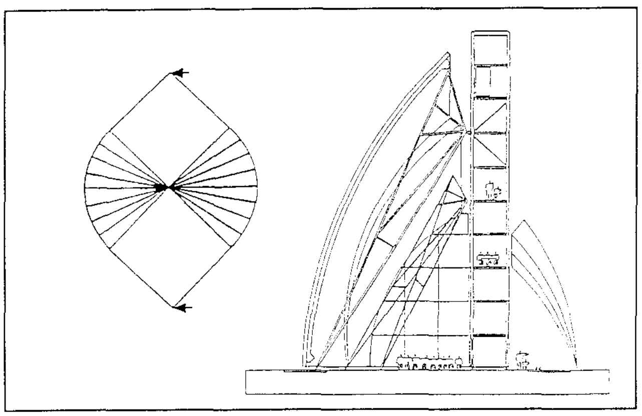




Figures 2a and 2b



Figures 3 and 4a



Figures 4b and 4c

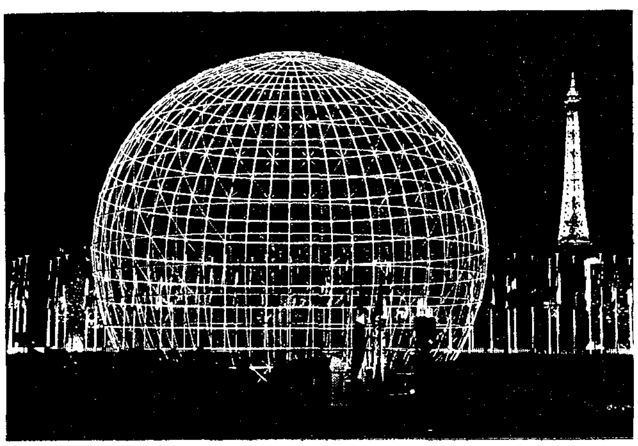


Figure 5

Danish pavilion for EXPO 92 in Sevilla. In the competition project it was necessary to choose minimal structures so that the pavilion easily could be transported from the production site in Denmark to Spain. The yield line pattern which we used for this project is shown in the broken glass. (Figure 4a). You notice the structure with two curved lines and the straight lines which also are known from the yield patterns. (Figure 4b). You can find the same principle in the sculpture bridge in Sophienholm, where you also find the connection between fracture and structure. In certain areas of the bridge the yield lines (which inevitably will arise) have been inserted beforehand in the construction.

The Symbolic Globe (Figure 5) is a pre-stressed minimal construction of aluminium and stainless steel consisting of more than 10.000 small parts. Contrary to the Tower of Babel, delegates gathered from all over the world to construct a symbolic globe in Copenhagen in 1995. It was built in six days. The event was the United Nations world summit on social development. Among others the secretary general of the UN Boutros Boutros-Ghali participated. He also signed the globe. The Symbolic Globe was later disassembled, transported to Paris, and reerected in front of the UNESCO headquarters, where it now stands as a symbol surrounded by all the flags of the member states.

In 1970, the old national bank in Stockholm was very ramshackle and Sweden arranged a competition in which I took part together with architect Gunnlögsson. We did not only work with the aesthetic and functional criteria but also with as optimal structures as possible to fulfill the tectonic criteria. By the way this project took the first prize. Together with architect Gunnlögsson we also won the competition of a church north of Copenhagen. In this case we followed another principle consisting of 120° angles (Figure 6). What you can gain from 120° angles you will see in the illustration as follows (Figure 7).

Here are shown different column profiles which all consist of the same amount of materials but are elaborated in different ways. In Figure 7a you can also see the carrying capacity for different column shapes. This is totally in accordance with my theory on minimal structures that contraction cracks, for example in drained clay, attend the 120° geometry. Figure 7b might represent the geometry in a canal or in a motorway in a bird's eye view. The most appropriate utilization of the material is also obtained here with 120° geometry, which has been found by help of membranes made by the soap film placed between two glass plates. You see the soap film attend the same principle with the 120° angle. A principle found by nature itself.

Let us stay for a moment at the soap film. Two circular wires have been lowered into soapy water and the result has been photographed: A minimal surface shaped as a catenary of revolution. The soap film surface was used to define the shape of a big tent construction which was erected to shelter the performance of Shakespeare's Hamlet at Kronborg in Elsinore. The diameter was more than 70 metres and the structure is like an umbrella being opened when it is raining but closed if the wind velocity is more than 14 metres a second. It was tectonics for movable structures.

If you shape a wire as a cube and dip it in soapy water the result is: The open cube. This cube is now situated in Tête Défense—Paris. Let's start with the tiny little and continue to the big which means from theory to practice. In 1982 architect Spreckelsen invited me to participate in an international competition to finish the historical axis in Paris with a building

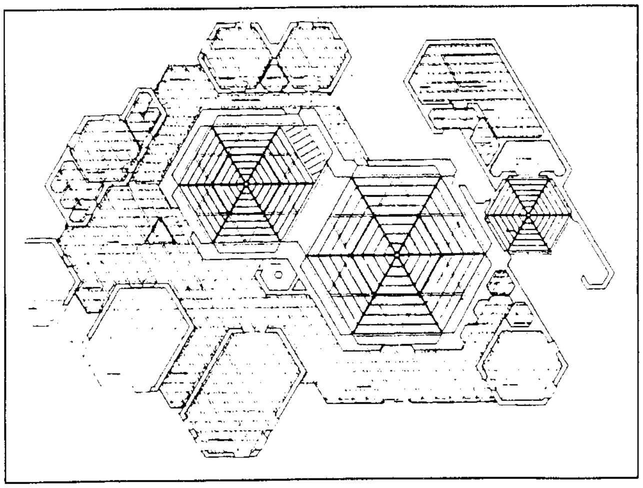
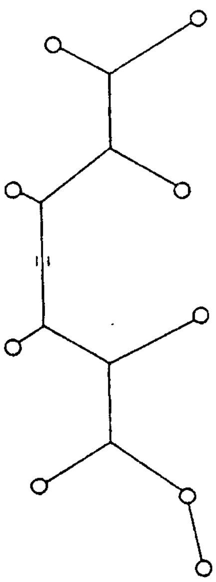


Figure 6



PROFIL	NAVN	BÆREEVNE
51 × 51	MASSIV	1750 KG
10, 100 × 100	HE-100B	5210 --
10, 75 × 75	FIRKANT RØR	5360 --
135 × 135, 10	90°-FLIGE	6400 --
10, 92.8 × 92.8	RUNDT RØR	7000 --
86, 43, 10, 149	120°-FLIGE	10600 --

Figures 7a and 7b

situated in La Défense quarter in Paris.

The difficulties in constructing anything at all in this area were enormous: First of all the underground is a labyrinth of tunnels for the metro, motorways, and railways. Next the CNIT-exhibition building with it expressive and dominating lines. It was necessary to find a construction independent and complementary. According to the program the aim was to create an international communication centre which not only was connected to La Défense quarter but also the Paris area and all the countries of the world. Many diagrams show the difficulties to fit in the functional demands for the centre, which the new building was supposed to supply.

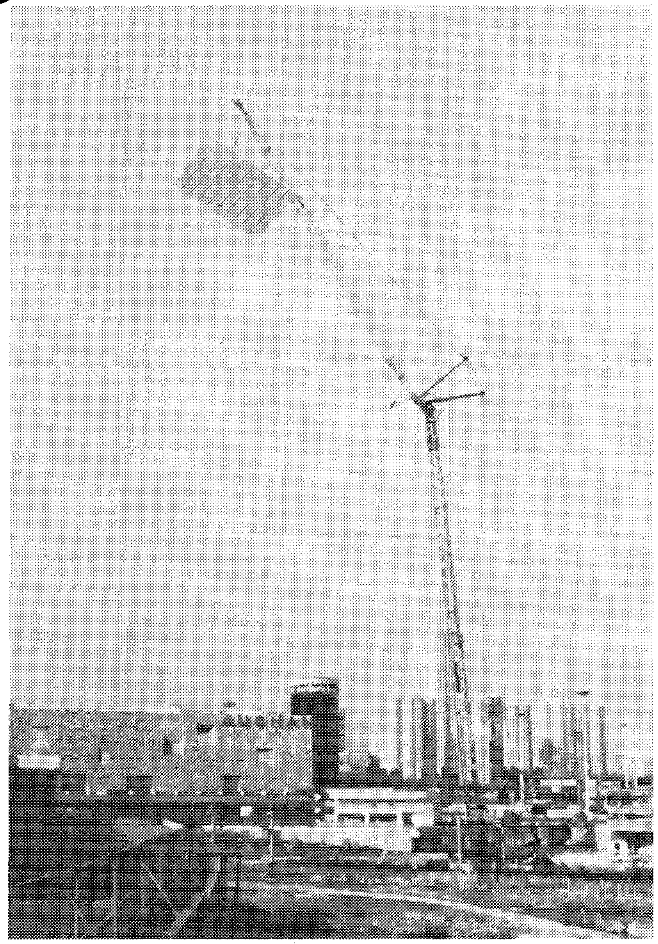


Figure 8

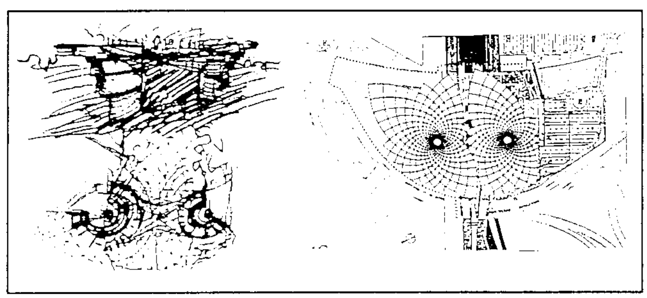


Figure 9

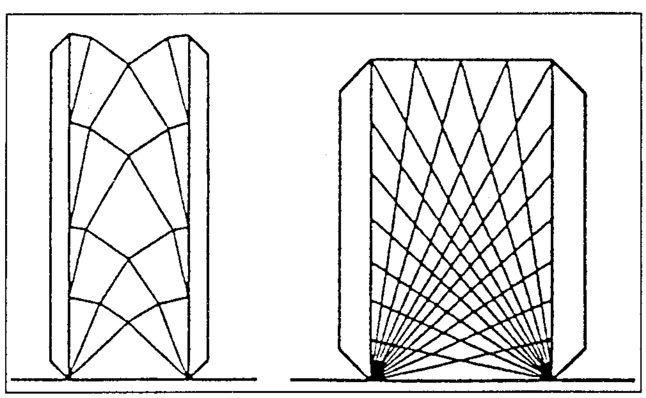


Figure 10

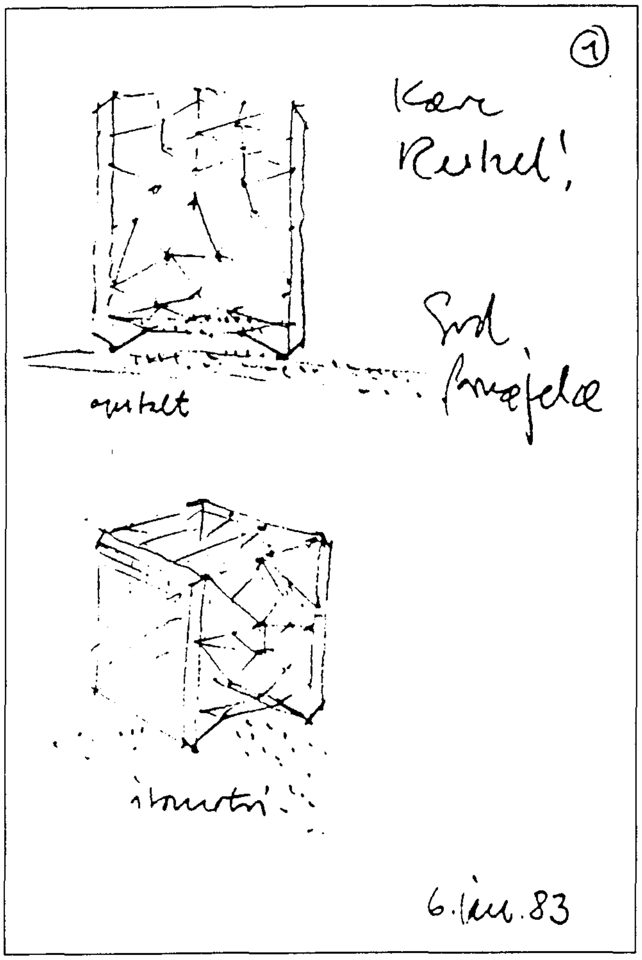


Figure 11

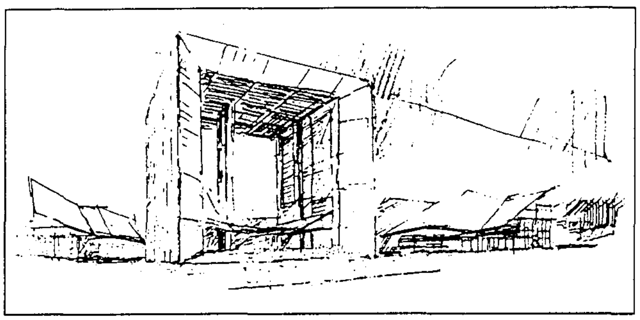


Figure 12

Figure 9 shows some rough designs made in a dialogue by Spreckelsen and me. We mailed the designs to each other. Both Spreckelsen and I began with mega-structures shaped as spirals. In my case they formed two towers through which the historical axis could continue. Some further designs from the architect show different solutions. One of these solutions was a big wall with many windows—shaped as a big punched card through which the historical axis could pass. I have preserved many sketches from this period of work where the solution of tectonic problems was essential. Figure 10 shows two different suggestions I worked out. Each building almost 300 metres tall was stiffened by minimal structures. The architect appreciated the idea and mailed me a letter on this subject the 6th January, 1983. The two sketches from the architect show the preshape for the open cube and inside a minimal construction—with socle but without roof.

But how to pass from two vertical buildings to an open cube? Notice that the architect was very interested in both the cubic form as an architectural element and in my experiences with minimal surfaces and soap films. Another inspiration for the choice of form was computer chips. The minimal structures between the two buildings were gradually changed into an isolated elevator tower and the so-called clouds which are folded constructions in glass and steel, suspended at a low height. And how find the manner of making holes in the bearing structures of the cube? To create space and cut through the mass if, well, that is the proper job for an engineer.

The cube consists of neither beams nor columns in the ordinary meaning of the word, but a megastructure with holes adapted to the ways of the forces and the size. The holes make the construction light, they are part of the function of the building, and they make it possible to get big space for exhibitions, cinemas, restaurants etc.

While elaborating the project for the competition the problem arose of placing the foundations between the mess of motorways, metros, etc. When I told the architect that the foundations demanded a turn of the cube about six-and-a-half degrees, he replied, very pleased, that this demand would result in an even better architectural solution.

In this form we presented our project at the international competition (Figure 12). The international jury and the president of the French Republic, François Mitterrand gave the 1st prize to the open cube. After the examination and after the press conference in May 1983 there was a discussion: How will the cube look seen from the Louvre and Champs-Élysées, through the opening in l'Arc de Triomphe de l'Étoile?

One day in August 1983 I was called to Paris to illustrate in la Défense exactly how the cube would appear in the end of the historical axis. The schedule I received was between the 4th and the 17th August. We planned a lattice work covering one fourth of the front edge of the roof to be lifted up. The weight was approximately 10 tons and the height 160 metres above.

You see the first stage of assembling the lattice-work. The big crane is being assembled and erected. Here the final stages before lifting up the lattice work. And now, at last, a temporary roof of La Grande Arche in the quivering air of Paris. After this successful experiment, green light for projecting and erecting the cube. Then followed the feasibility study with defining all parts of the project.

Cooperating with the French firm COYNE et BELLIER I made detailed calculations of the forces of the cube. By calculating you are able to spot any weak point and discover the deformations which will arise. For reasons of function and form it was necessary to be loyal to the philosophy of the competition project and refrain from making odd holes. You can imagine the consequences. You are now going to see a series of pictures showing the progress of work at the construction site of La Grande Arche. The contractor was the French firm BOUYGUES. All the blue slides show the original ideas while the others show the realization. And then the facades with all the floors, level by level—instead of building the megastructure first.

And 7 years after start of the competition La Grande Arche is completed. Unfortunately the idea of a centre of

Figure 13

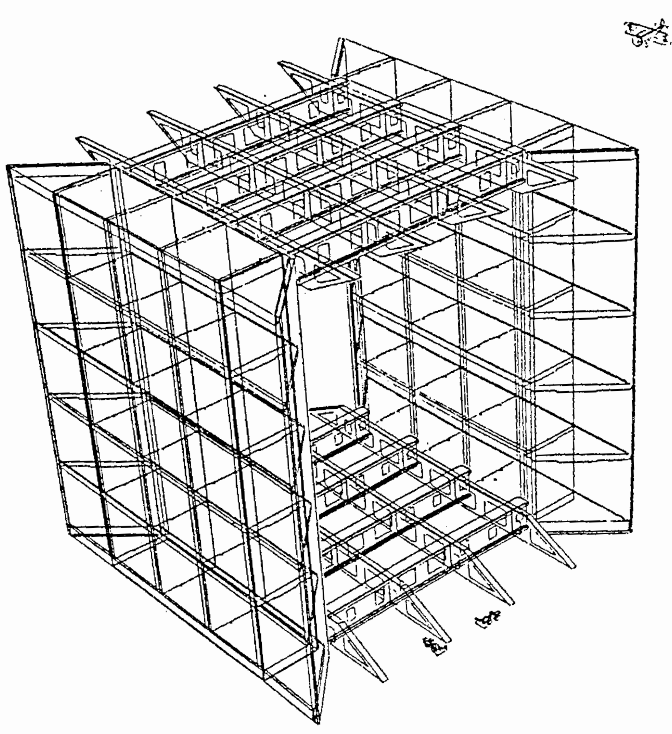


Figure 14

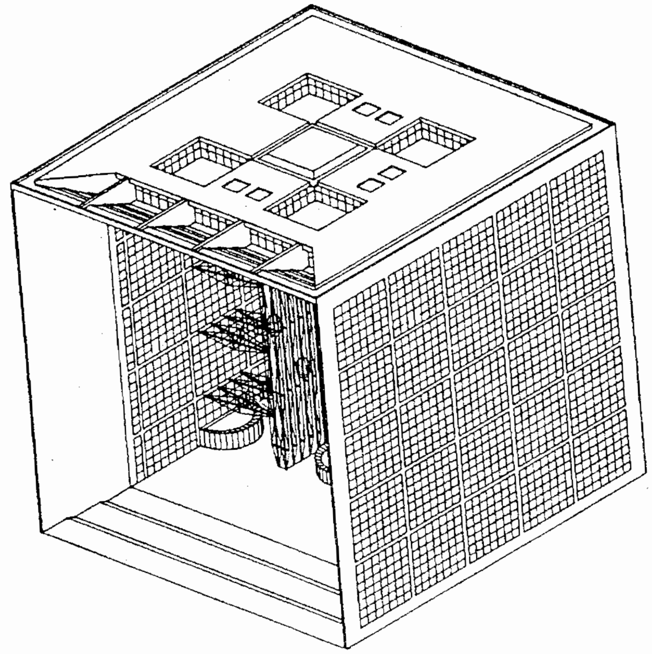


Figure 15

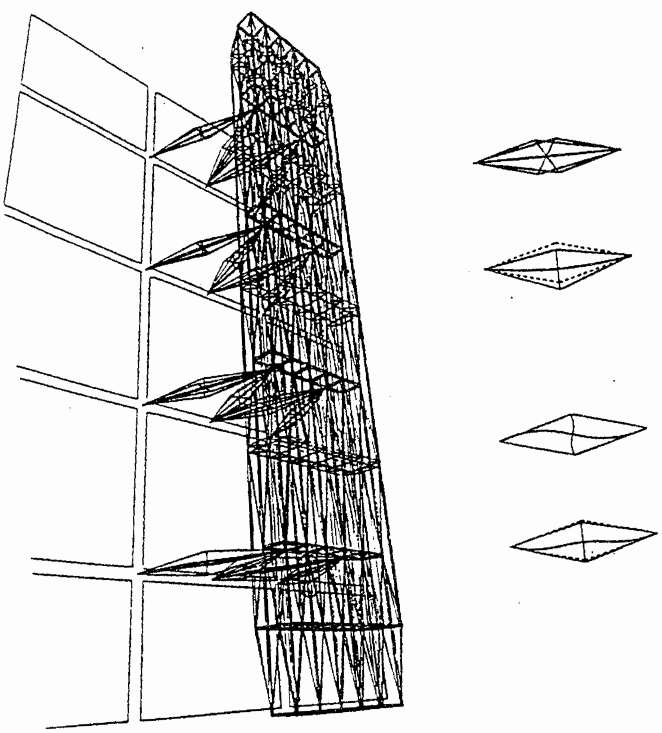


Figure 16

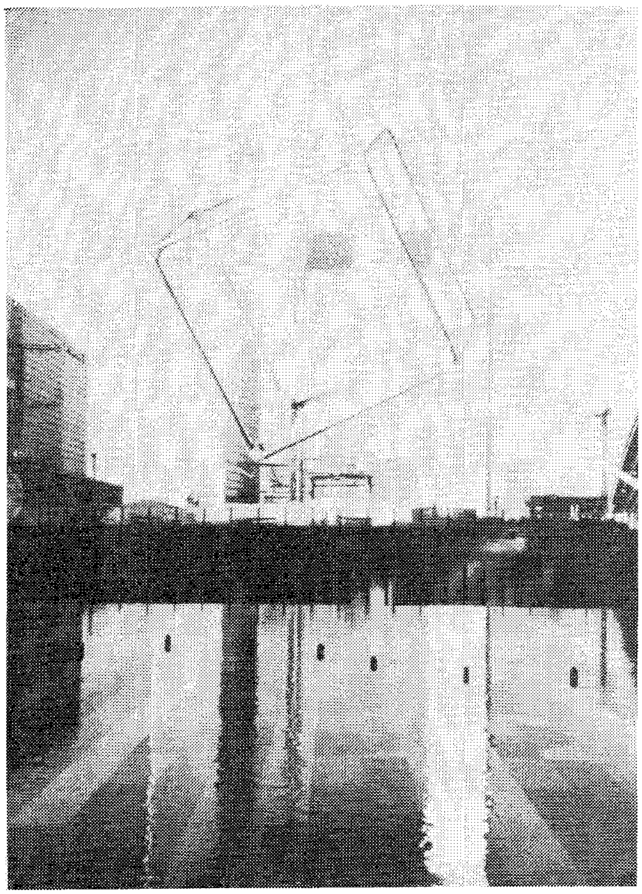


Figure 17

communication was abandoned—but fortunately the idea of a minimal structure inside the cube was carried into effect by the construction of the external elevator tower. You see clearly the minimal structures in the elevator tower with the structural design of the column tensioned by wires. The optimal pre-stressing gives as a result a bearing capacity four times bigger than the bearing capacity of a non-stressed column. The first test of the elevator tower. The cabin runs in the interior of the minimal structure consisting of the wire-tensioned columns. The inauguration of La Grande Arche in 1989 was attended by the presidents of the seven greatest countries of the world. For me as the engineer it was a satisfaction to know that nobody doubted the resistance of the structure against fracture, and to have employed my philosophy of fracture and form.

ILLUSTRATIONS

KHR architects/E. Reitzel: Figure 4
Gunnlögsson & Nielsen/E. Reitzel: Figure 6
J: O. Spreckelsen: Figure 9b and Figure 11
Competition project Tête Défense: Figure 12
SAEM, Tête Défense: Figure 15
All illustrations not mentioned above are executed by the author.