Design and erection of a hanging timber shell in Vienna

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Conception et réalisation d'une coque suspendue en bois à Vienne

Entwurf und Bau einer Holzhängeschale in Wien

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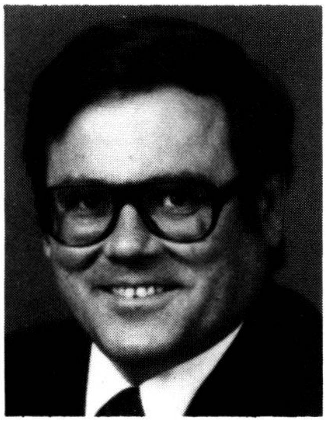

Julius Natterer was born in 1938, received his diploma as a civil engineer at the University of Munich. Since 1968 he has been directing his own engineering office in Munich, adding in 1983 a second office in Switzerland. With his group he realised more than 800 timber structures mainly in Central Europe.

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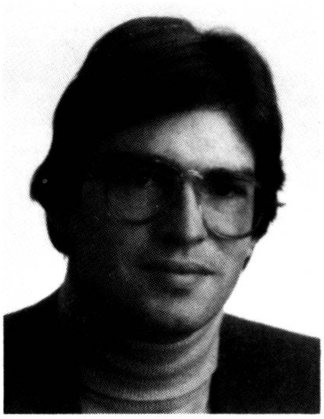

Wolfgang Winter was born in 1948 and holds diplomas in Civil Engineering and Architecture from the University of Stuttgart. As project engineer, he was involved in the design of the Vienna Structure. Since 1984 he has been first assistant of the Institute of Timber Constructions in Lausanne.

SUMMARY
The article describes design and erection details of a suspended timber shell for a recycling plant in Vienna, showing that timber constructions can satisfy modern structural requirements.

RÉSUMÉ
L'article décrit la conception, l'étude et la réalisation d'une coque suspendue en bois pour une installation de récupération de déchets de la ville de Vienne. Il montre que les constructions en bois peuvent satisfaire les conditions les plus difficiles.

ZUSAMMENFASSUNG
Der Artikel beschreibt Entwurf, Berechnung, Konstruktion und Bau einer Holzhängeschale für eine Abfallwiederaufbereitungsanlage in Wien. Er zeigt, dass Holzbauwerke die schwierigsten Bedingungen erfüllen können.

Introduction

In Europe the image of timber construction is characterized by historical structures. For example, the Swiss chalets, the timber framed houses and old wooden bridges form part of Europe's history.

During the past ten years several outhstanding heavy timber structures were erected. These structures were not always cost efficient but aesthetics and other architectural values have influenced the decision to use wood. Examples are churches, municipal facilities and sport buildings

In Europe, few people realize that large timber structures can compete with the most advanced techniques in concrete and steel

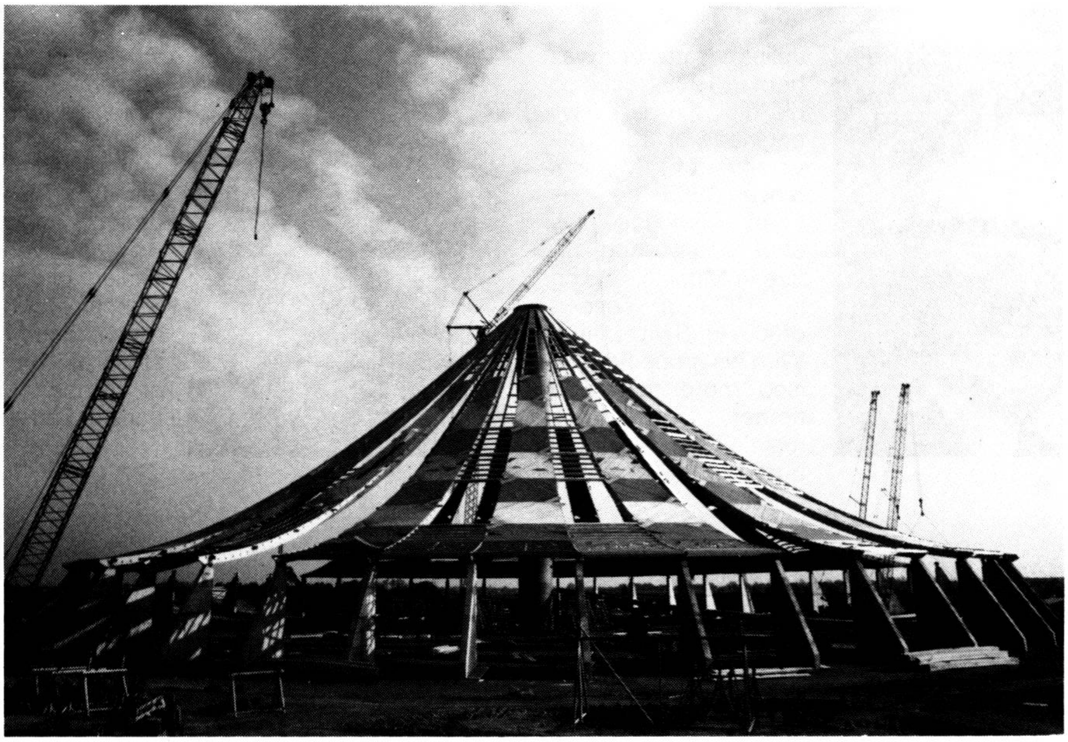

Fig. 1 : The hanging timber shell in Vienna during construction.

In the United States such competition was proved to be possible by the completition of the trussed dome in Flagstaff, Arizona with its record span of 150 m. (502 ft).

Modern timber structures in Europe joined the "long span club" in 1980 with a hanging shell erected in Vienna by engineers and contractors from Austria and West Germany.

This industrial building was designed and built in less than one year (from the first sketches to the last nail). Furthermore the competing solutions included a well developed cable-net in steel.

The building has a tent shape and a central tower in concrete creating a circular ground plan of 170 m. in diameter (560 ft).The maximum span is 85 m. (280 ft) and the building volume is 580 000 m3 (20,5 million cubic feet).

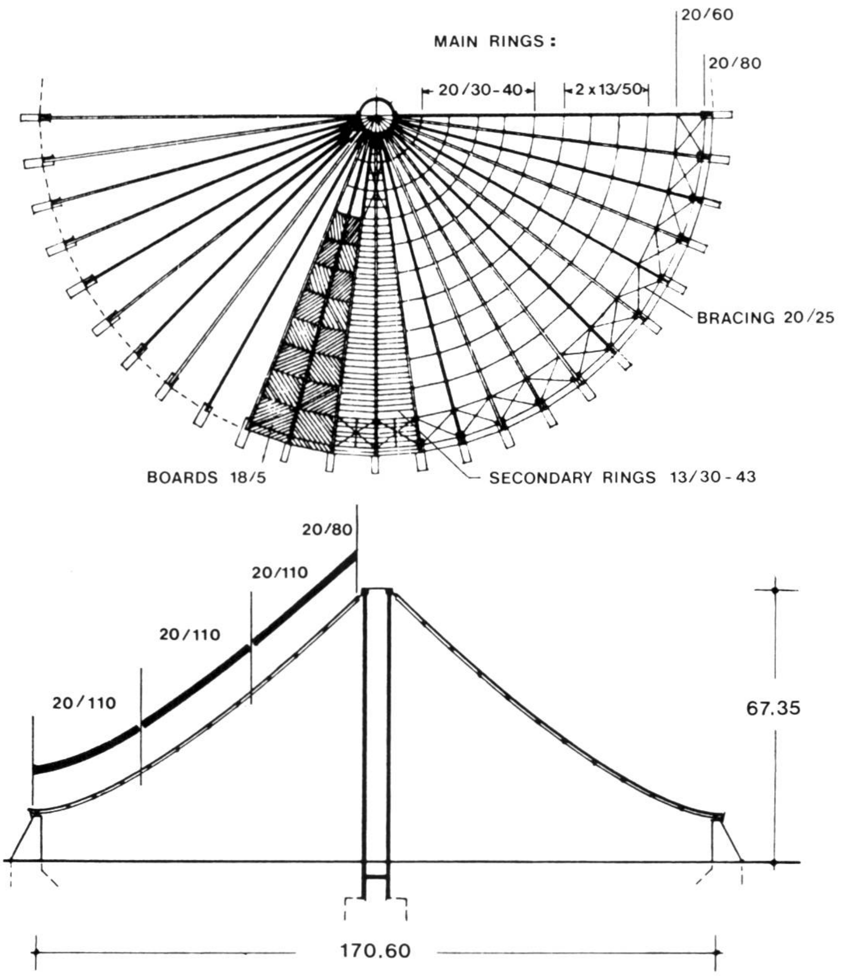

Fig. 2 : Ground plan and transversal section of the structure.

<u>The function of the building</u>

Recently, the city of Vienna developed a new system for solid-waste treatment. In most European cities municipal services are responsible for solid-waste treatment. The City of Vienna engaged private firms to participate to this task and awarded them a long term contract for treating a fixed volume at a set price. In the way the private company was able to develope a long term strategy for treating the waste.

Existing technologies for solid-waste treatment were studied throughout the world in order to determine the economics of selling recycled waste.It was observed that available mechanical recycling systems are not yet very efficient although development is taking place. Therefore, a priority requirement for the hall was that it had to be multifunctional and easily adaptable.

The architectural design was guided by the following criteria :

- create a covered volume as large as possible with a minimum of columns in order to permit future utilization of machinery of unknown dimensions.

- integrate the chimney (68 m. 223 ft) in the building.

- create a volume with good natural ventilation and no mechanical ventilation.

- create a unique form for the building to complement the "futuristic"conception of solid-waste treatment.

- the site was a flat industrial area east of Vienna near the airport, away from residential areas.

The chosen form of a circular circus tent with a concrete tower as chimney satisfied these criteria in the best way.

Preliminary design proposals

As is the case with most projects, the timber solution was not present at the beginning of the study. At first concrete and steel solutions were studied. It was recognition of some major disadvantages with these types of structures that the timber solution was considered.

- the concrete solution :
  the first solution in concrete accomodated the idea to put grass on the roof (a proposal from the famous Austrian artist Hundertwasser). Understandably, this solution proved to be unrealistic due to the enormous dead load.

- The cable net solutions :

The first preposal included a radial structure with linear Jawerth-trusses fabricated using cables. This system was too complicated for roof supporting members.
The next solution employed a cable net and a structural configuration previously used for the roof of the Olympic stadium in Munich and for big cooling towers. This solution was detailed entirely before it was rejected at the last moment by the fire authority of Vienna. A fire resistance of 30 minutes could not be guaranteed by the steel cables unless very expensive protection features were adopted.

- The timber solution :

It was only at this time in September 1980 that timber designers were contacted with production scheduled for 1982.
A similar structure in timber had never before been erected, but one of the authors (J. Natterer) had already designed and proposed similar projects for Munich Olympic Games. A very economical solution in timber was rejeted at that time because the television companies preferred a transparent roof. This existing design shortened the whole project for Vienna including static calculation and demand for offers to only 6 weeks.

The design of the timber shell

The main elements of the timber roof are 48 hanging ribs. The geometry of these ribs was designed to have only tension forces and no bending moment under dead load. For this reason the shape is similar to the diagram of the bending moment under a triangular load - a third order parabolic curve. The parabolic ribs were placed in such a way that in the lower part of the shell, water does not stay on the roof. Therefore the rib starts with a slope of 6%.

Under uniform load, the ribs work like cables. Non-uniform loads such as wind or unsymmetrical snow loading produce bending moments in the ribs, and it was these moments that determined the dimensions of the ribs.

In Europe, the maximum length for road transportation of structural elements cannot exceed 50 m. (164 ft). Therefore, the elements to be assembled on site. Considering that the assembly transmits bending moments, a hanging beam is more appropriate terminology than a timber cable. For this reason the cross-section of the ribs was adapted to variations in bending moment, changing from 20/110 cm (8/43 inches) to 20/80 cm (8/31 inches) at the upper suspension.

In order to ensure that load carrying behavior resembles a shell, the hanging ribs were connected using 11 circular rings. The elements of these rings were assembled by special details, thereby permitting the transmission of compression and tension around the circular rings. These rings were placed on 7.4 m. (24 ft) centers.

This configuration proved to be an efficient method for carrying unsymmetric loads and for distributing them to several ribs. Alone, those ribs are too flexible when they are subject to unsymmetric loading.

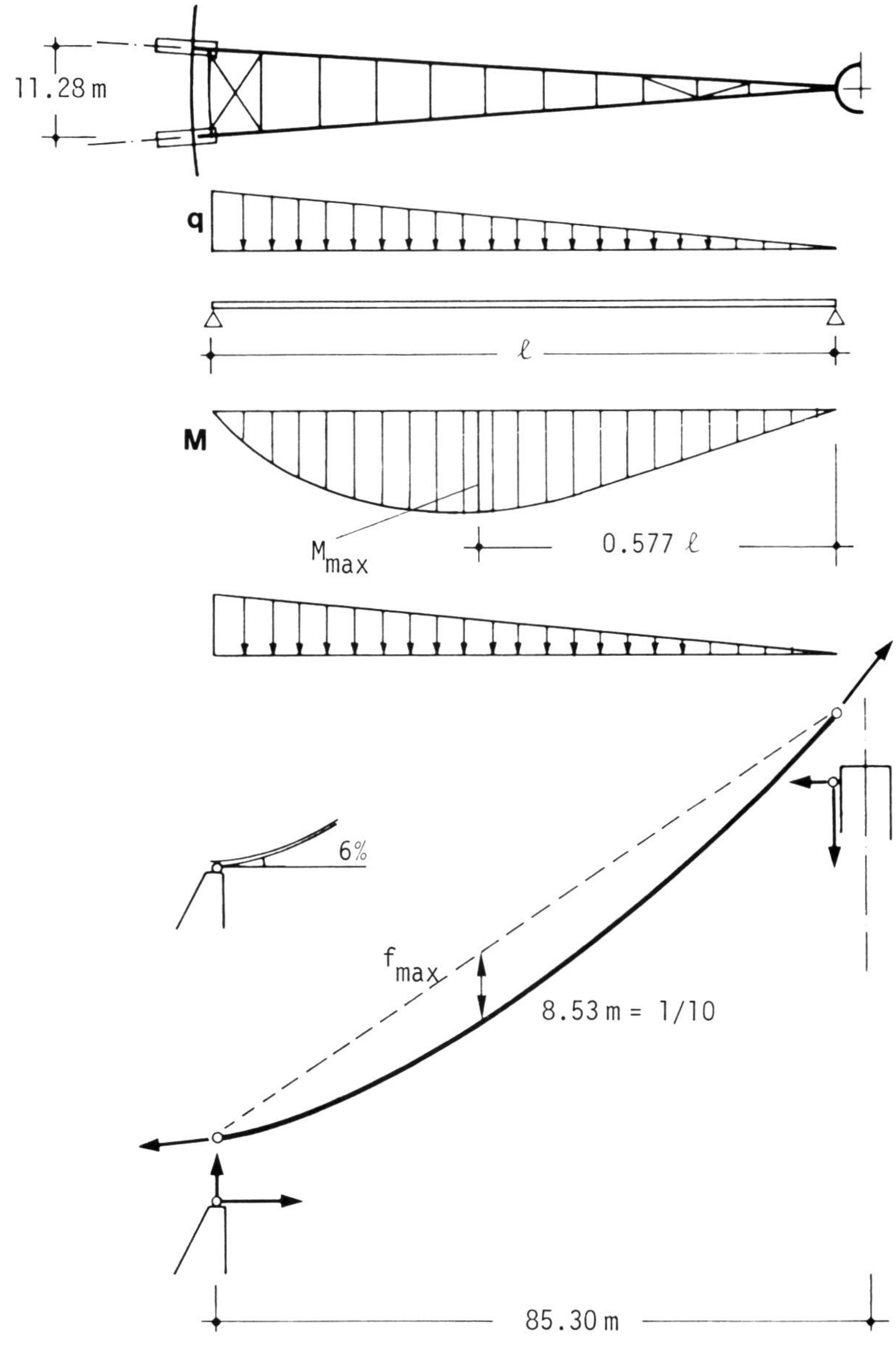

Fig. 3 : Determination of the shape of the ribs

A shell requires more than ribs and rings; elements wich provide shear stiffness are also needed. This stiffness was provided by diagonal placement of the roofing boards. In the lower part of the shell these boards were not sufficient to transmit the shear forces. Therefore, additional diagonal members were used in this region. In the upper part ventilation requirements preclude roofing boards, here diagonal steel cables ensure shear transfer.

Foundation problems

The most difficult and most aspects concerned the foundations. As the timber to concrete connection consumed more time than designing and calculating the timber shell itself.

The rib support had to be 11 m. (36 ft) above the ground because trucks enter the hall. The transmission of horizontal forces from the ribs to the foundation by means of a contilever of 11 m. presented a difficult problem.

One solution incluted stiffening the tower part of the roof woth a ring element which distributes the forces to the 48 foundations. This system requires a flexible connection between the shell and its foundation. Hinged timber columns were proposed but these were rejected because of the risk of truck collisions (Fig. 4).

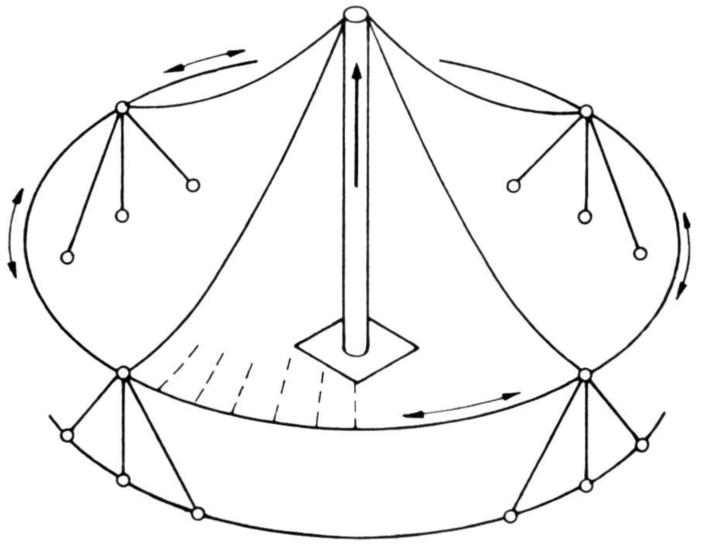

Fig. 4 : Structure with a lower circular ring. (No horizontal loading of foundation).

Finally, it was the fear of unknown transmission of forces between the concrete foundations and the more flexible timber structure which governed the decision.

Each rib was fixed on a large triangular concrete disk transmitting the entire horizontal force carried by one rib. Statically, this type of foundation is not very efficient because the total force per support is much higher than for a lower-ring solution.

The structure is not a true shell since the linear transmission of forces within the ribs is substantial. These horizontal forces arise from unsymmetric loading. A large problem related to this system was the determination of the loads carried by the supporting concrete structure

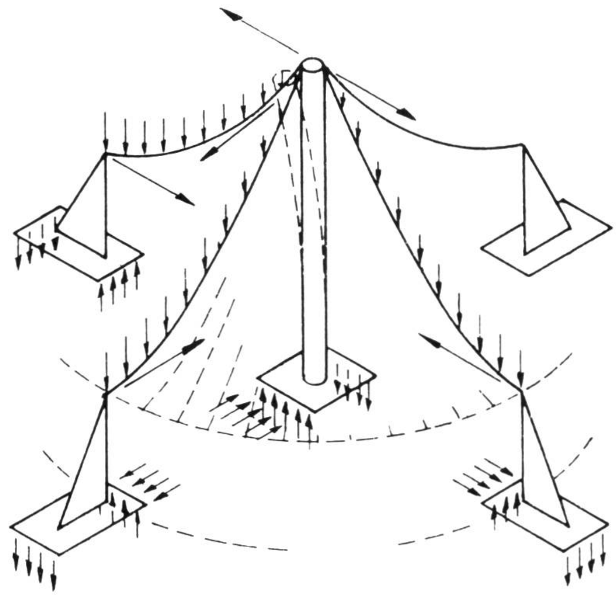

Fig. 5 : Structure with the suspension ribs a achored to each foundation

Determination of the loads

It is very difficult to determine the loads for such an unusual building (span and geometry) by using the existing building codes. Snow and wind forces are particularly difficult to quantify.

Therefore, a model was examined in a wind tunnel. The results indicated that the wind effects are less important than the codes presume for cylindrical forms. The maximum compression factor was 0.2 and the maximum suction 0.8 (Nevertheless, wind and unsymmetric snow loading were the critical load cases).

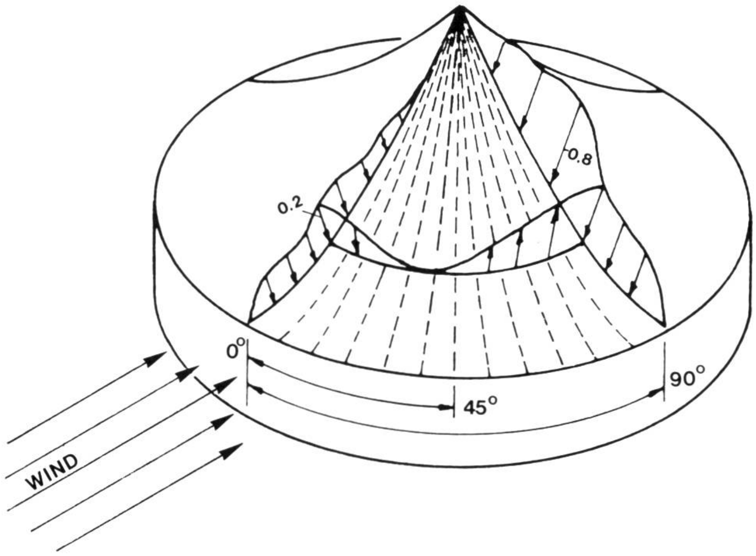

Fig. 6 : Calculated load case wind

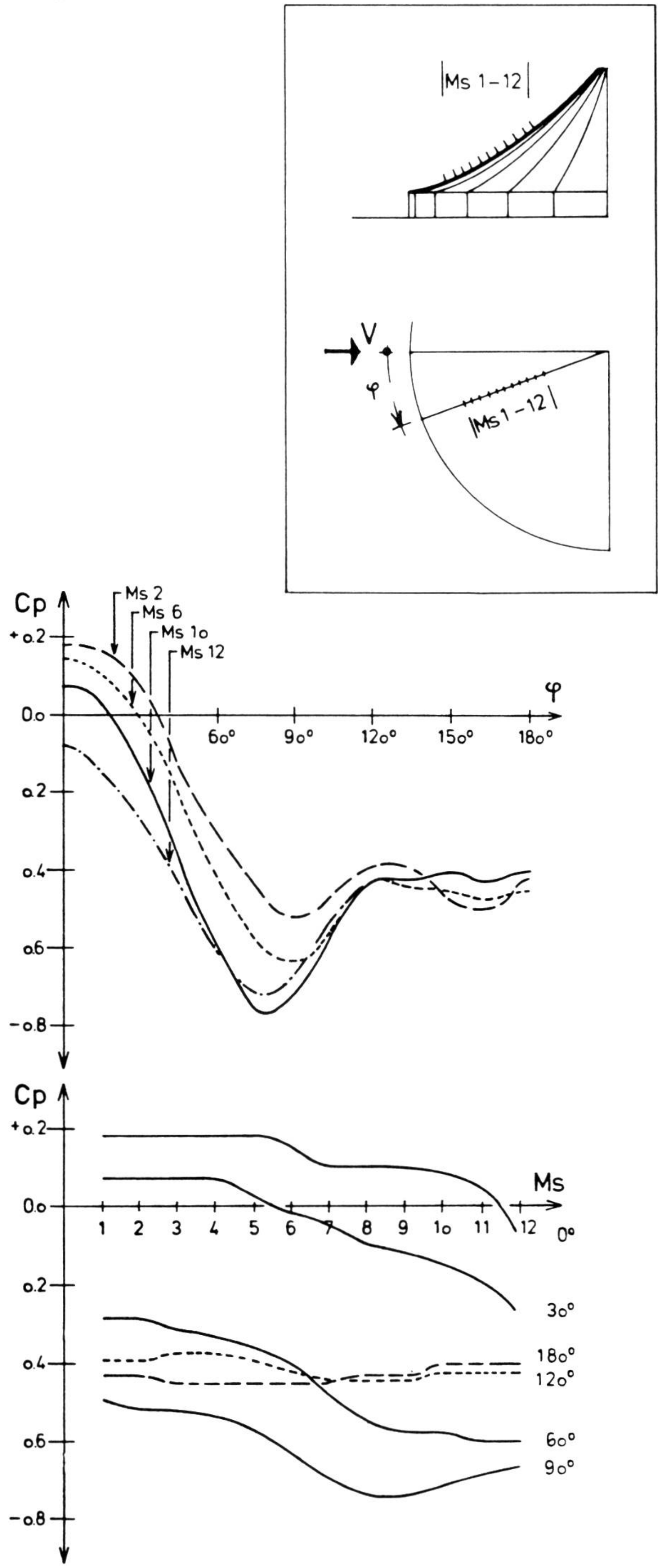

Fig. 7 : Results of the test in the wind tunnel.

Codes specify a uniform snow load of 75 kN/m2 (15.5 psf). The unsymmetrical snow load of 50 % of the maximum snow load in a given position and no snow elsewhere. The effects of sliding snow are not covered by codes. The effects are obviously important considering the conical form.

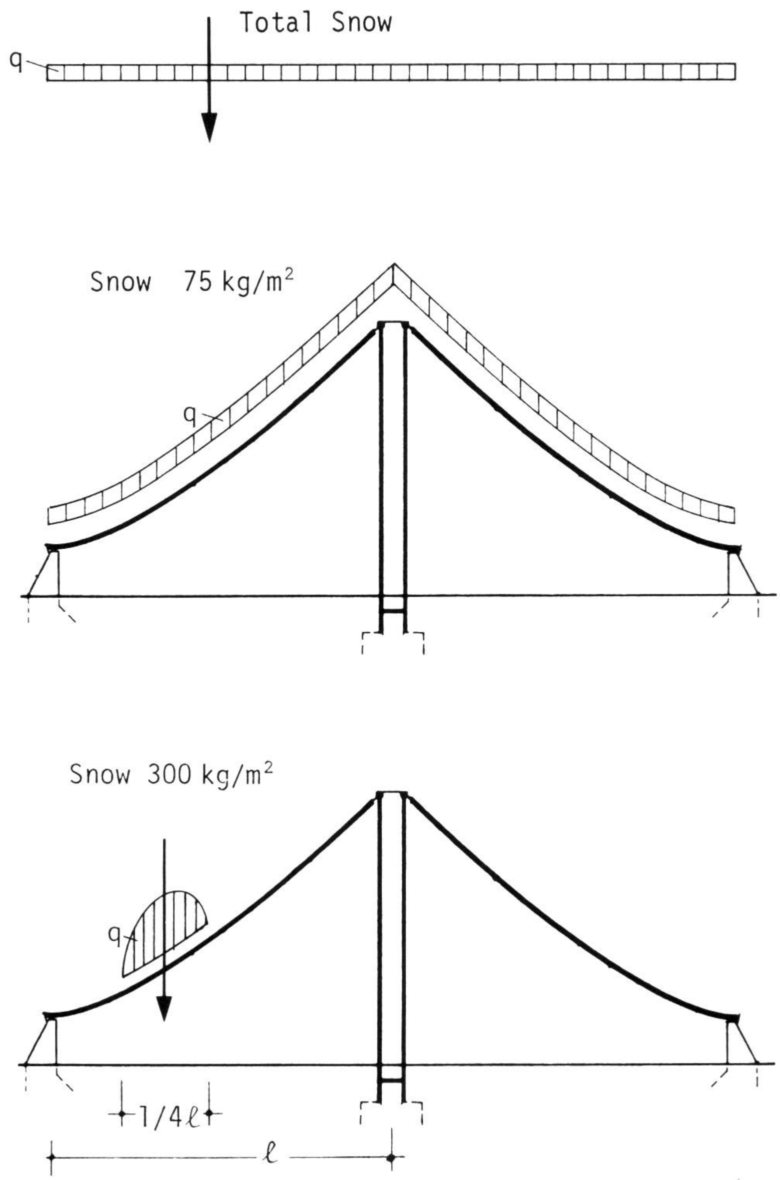

Fig. 8 : Calculed load case snow

A conservative pratical approach was adopted. By experience it was observed that snow concentration in windy conditions occurs at 45 degrees to the wind direction where there is the least suction. It was assumed that a concentration occurs on 25 % of the entire surface at maximum loading. Furthermore effects sliding snow were assumed to concentrate this loading in the lower region. This snow loading was superimposed on the maximum wind load.

Static calculation

For the static calculation a computer programm developed by the Swiss Federal Institute of Technology in Zurich was employed. The structure was modelled using 880 bars and 629 nodes. We did not introduce all circular rings, 11 instead of 44, and only these rings were dimensioned to carry horizontal circular forces. The diagonal boards were modelled using one concentrated diagonal bar.

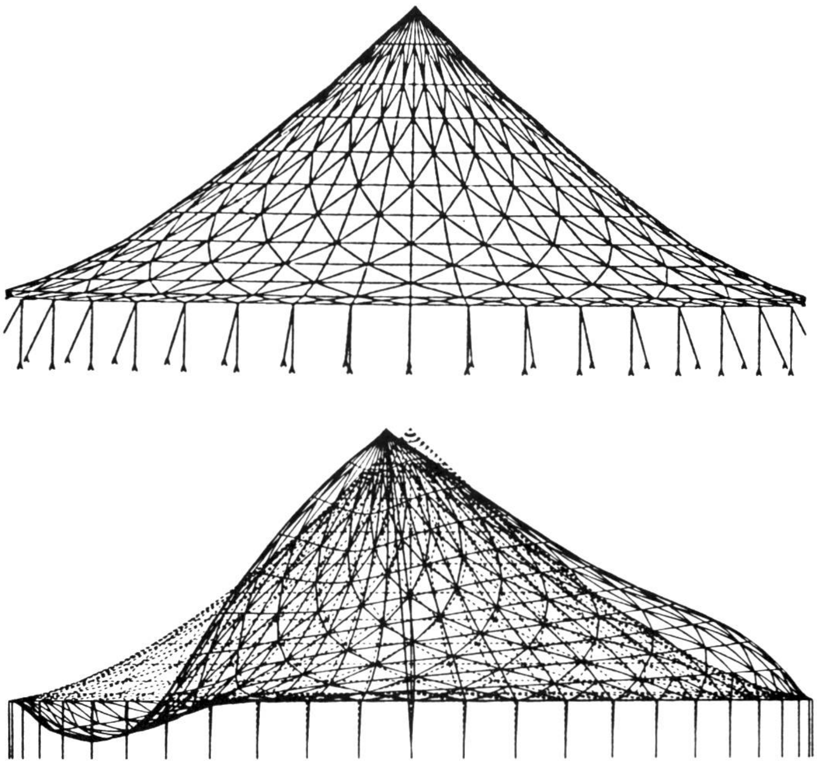

Fig. 9 : Computer modelling of the structure and deflection under the worst load wind and snow.

The influence of deformations on the supporting concrete structure and the connection details was difficult to estimate.

A small horizontal deflection of the concrete tower increases the stresses in the ribs, and horizontal movement of the concrete triangle increases loads carried by the circular rings.

The deformation behavior of large nailed connections under short term such as wind or nonsymmetric snow loading is unknown. Such details connect the circular rings at each rib and their stiffness has an important influence on the static behaviour of the entire structure. Large deformations in the circular rings reduce the forces in the rings and increase the loads carried by the ribs.

The exact shape of the ribs of the structure could not be estimated although they were produced in a determined shape. After erection the ribs deflected before the shell effect was created by the rings and the diagonal boards. In order to account for such deflection the stresses in the ribs under dead load were calculated without the shell effect, and the deformed shape of the ribs was used for the calculation of the stresses due to wind and snow loading in the shell model.

Using probable maximum-minimum values more than 20 calculations using different combinations of deformation parameters were carried out. Different models were used for the calculation of the deflection of the concrete elements since the ground properties had a large influence on the stresses in the supports.

For the determination of the cross section and connection details, the worst values were used.

Construction details

The loads carried by the nodes varied between 1 and 150 tons. These loads cannot be transmitted within a reasonable space using classic connectors such as bolts or split rings.

The most effective method of transmitting loads between wood elements employs steel plates (5-10 mm. thick = 1/4 to 1/2 in.) which are nailed on the timber elements with large, high strength nails with a diameter of 4 to 6 mm. (3/16 to 1/4 in.) and a length of 50-60 mm. (2 in to 2 1/2 in.). The steel plates are connected with large diameter bolts and introduce the loads into the timber by means of the nails.

Nailed connectors can transmit high loads. The suspension of the ribs on the tower is achieved using two nailed plates (60 to 120 cm.) (24 in./47 in.) with 560 nails on each side.

A special detail was developed for the intersection between ribs and rings where the ribs continue and the rings are interrupted. The loads in the ring direction are tension and compression, up to 50 tons. Compression cannot be transmitted using the ribs since they are weak in the axis perpendicular to the grain.

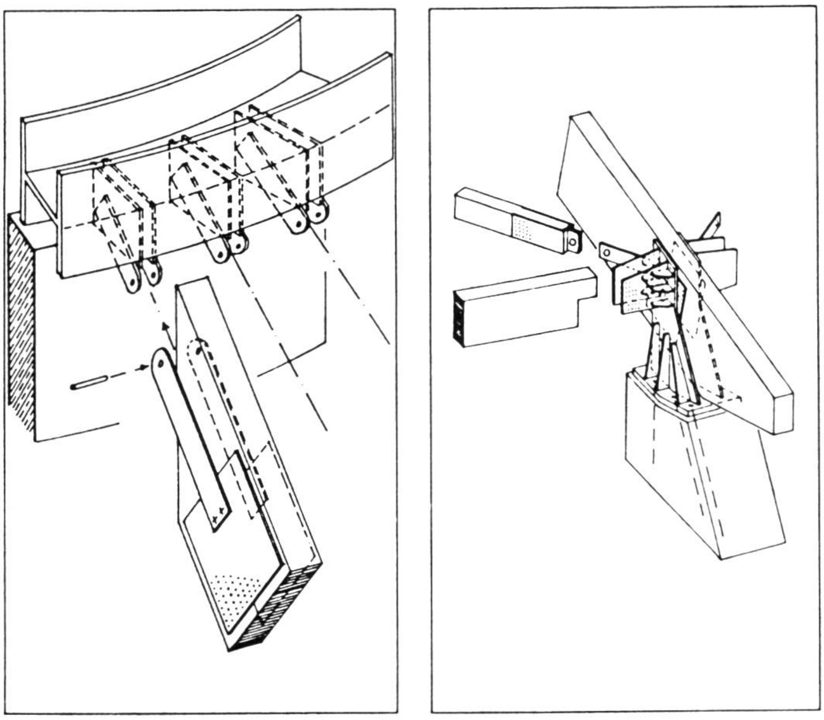

Fig. 10 : Suspension of a rib to the tower and connection of a rib to the foundation.

Special welded element which transmit compression using steel tubes passing through the ribs were designed to resist compressive loading.

Special connections were developed to connect the 40 mm. (2 in.) boards with the ribs and the rings. The boards were finger-jointed because it was not possible to interrupt them. The boards serving as diagonals in the shell network must transmit high tensile forces between the ribs, the rings and the boards in the next quadrant. Nailing them directly to the ribs was not possible because the tensile stress perpendicular to the grain was too large. A thin steel plate (1 mm) was first nailed to the top of the ribs to transmit the forces from field to field directly.

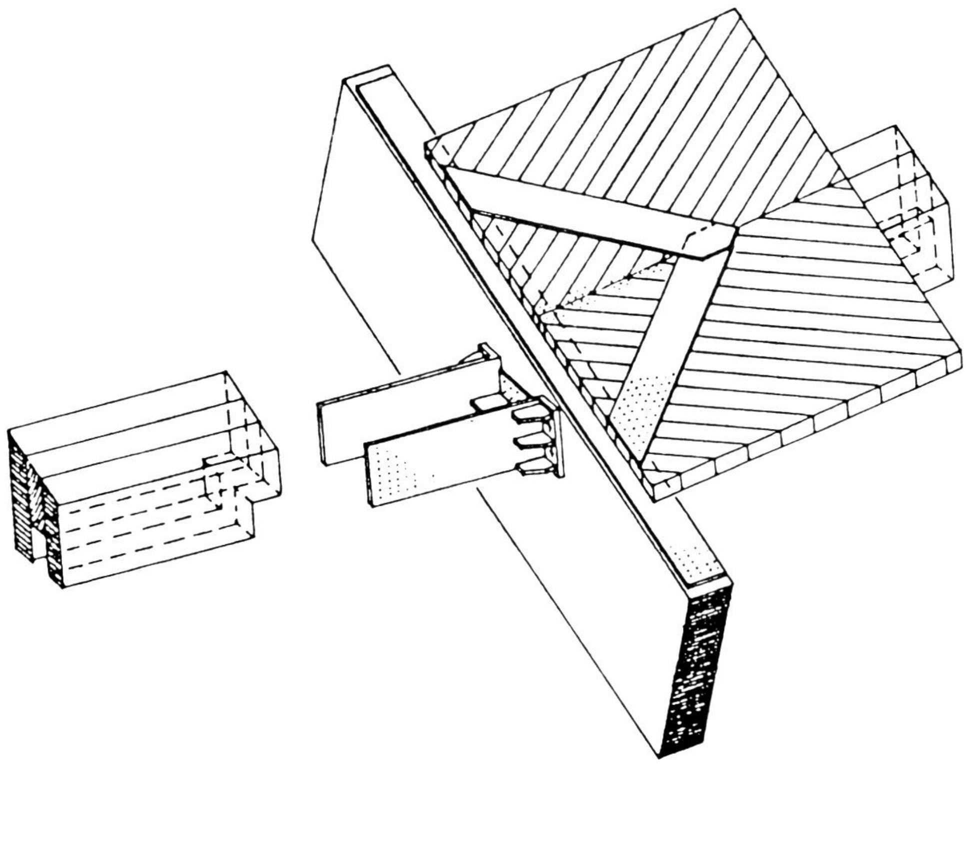

Fig. 11 : Connection between ribs, rings and boards.

Erection

Nearly every element was prepared in the shop on site. Only the glulam elements and the welded steel connectors were prefabricated. This is an advantage of timber structures. Large halls are not needed. Small firms can fabricate on site using simple machines. In the case of the Vienna structure , several small carpenter firms combined forces and provided 40 000 hours of labor in a few weeks with only 70 workers and without expensive equipment and machinery. When compared with similar projects which employ concrete such efforts are small.

The first erection mode which was taken in consideration was to prepare the whole structure on the ground for subsequent lifting. The disadvantage was the fact that the ribs would have to be moved on the ground.

Finally it was decided to prepare a triangular shell element with two ribs on the ground with all ring elements between the ribs and the boards fixed. Only elevators were needed for this kind of preparation.

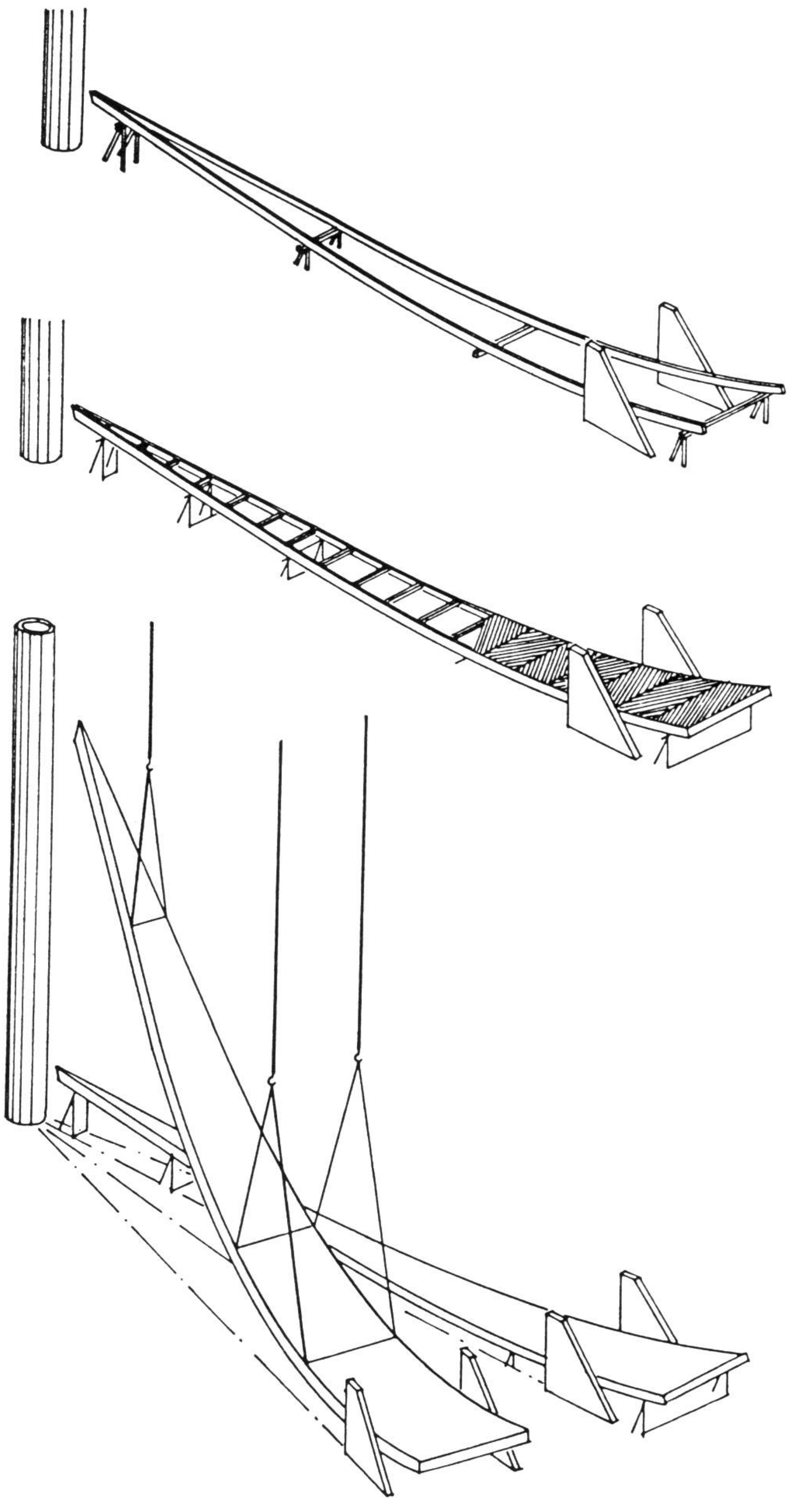

Fig. 12 : Erection.

The lifting of one of these elements with a weight of 60 tons was studied on a reduced scale (1:20) with toy-cranes. On site three mobile cranes (one 200 tons, two 130 tons) were used simultaneously to lift the shell element and move it into final position. A special suspension system was developed to achieve the precision required due to the small play in the fixing bolts.

The firms demonstrated that they are able to prefabricate in a shop on site, elements of more than 100 m. (328 ft) in length to meet close tolerances. Such performance is impossible for in situ concrete and requires shop prefabrication for steel construction.

The elements were lifted in such a way that the tower was not loaded eccentrically. The ring elements between the prefabricated triangles were lifted using a hydraulically operated platform. All boards were lifte into the roof and subsequently cut and fixed in place.

Some statiscal data :

Surface on the ground :	27'000 m3
Volume :	580'000 m3
Glue-lam :	1'900 m3
Sawn timber :	100 m3
Boards :	1'020 m3
Steel connectors and bracing :	270 tons
Nails :	3 million
Design :	12 weeks
Erection and site fabrication :	6 weeks
Total planning and realisation :	13 months

Contractor :	Rinter AG Vienna
Architect :	L.M. Lang, Vienna
Engineer, concrete :	Jakubec, Vienna
Engineer, timber :	Natterer, Munich
Control engineer :	Kugler, Vienna and Mencik, Vienna.

Closing remarks

In completing this structure, the timber construction industry in Europe has demonstrated its technical ability and its organizational skill to large spans and huge volumes which can be enclosed using timber structures quickly and economically.

The structural hanging shell with bending stiffness has proven its quality. It can be used for other types of buildings requiring smaller or larger spans.

Timber construction can satisfy modern structural requirements such as long spans and large surfaces using tension elements. Which material is more suitable to solve the problems caused by the goemetry and the connection details of these structures ?

Timber can be easly cut and assembled on site. It is resistant to chemical attack and fire, and it can be produced using a minimum amount of energy. Timber construction could become much more important in the future than it is today.

In Europe, this first project of a long-span shell has shown that we need to learn more about the behavior of complex timber structures. This is understandable considering that for 100 years many generations of scientists and engineers contributed to the basic knowledge of the structural use of concrete and stell. Heavy timber constructions were only studied in Europe for short periods during the two world wars.

Much research is needed to ensure that an engineer knows as much about timber as he knows about concrete or steel. Timber is one of the most versatile and forgiving materials; if we want to use it in an efficient way, we have to make substantial efforts to develop theoretical models, testing methods, and creative applications.