# Design for Dismantling and Reuse of an Exhibition Pavilion, Germany

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## Introduction

From June to October 2000, Expo 2000 in Hanover, Germany, explored the theme of man, nature and technology. Spain participated in this last universal exhibition of the millennium with the intention of surprising the visitor. One of the keys of this intent was the design of the actual pavilion, the project developed as a result of a competition.

## Architectural Design

From the outside, the spectator becomes aware of a building with the shape of a prism, supported by a large number of pillars (*Fig. 1a*). The façade of the building is panelled with cork, has no windows and its surface is broken only by a few crevices. Entering the building by any of the openings between the supporting pillars (*Fig. 1b*), the visitor finds himself in an interior square (*Fig. 1c*) that, by its size (44.9 × 50.6 m) and illumination, both from the space between the pillars and from a central skylight (situated about 10 m above the floor), by the materials employed and the beds of plants, is designed to awake his feelings for the quality of life in the Mediterranean region. The roof of this square, in the form of a trough, constitutes the support for the exhibition areas (*Fig. 2b, c*) and, through a secondary structure, for the horizontal platforms, which give visitors access, reached from the square by a ramp. The roof structure and the outside walls are erected over this principal element, the trough.

## Structure's Boundary Conditions

Many conditions have to be met in the conceptual design of a building. In the present case, apart from the normal conditions resulting from the need to interpret geometrically the architectural and functional requirements, particular conditions had to be considered:

- The theme of the exhibition suggested that the materials and the methods of construction should respect the environment.
- The organisers of Expo 2000 stipulated that the site should be returned in its original state after the exhibition.
- The owners of the pavilion wished to be able to dismantle the pavilion after the exhibition and reuse it in Spain.

The combination of all these conditions had serious consequences with relation to the selection of the materials to be used in the construction, the structural concept and detailing, and the methods to be used in its manufacture and assembly. Particularly, the desire to reuse the structure after the exhibition dominated the design concept.

## Conceptual Design

The structure of the pavilion can be easily divided into two areas: the service area and the show area (*Fig. 2a*). The two areas cannot be considered separately, since the overall concept of the structure leads to an interaction between the two.

The framework of the service building consists of steel columns and composite beams. The composite action of the steel girders and the prefabricated concrete slabs (characteristic compressive strength: 35 N/mm²), whose standard size is 4.6 × 2.3 × 0.12 m, is achieved by prestressed bolts (*Fig. 3*).

The main support element for the show area, a false truncated pyramid or trough is formed by inclined planes and the so-called upper and lower chords. There are needed for an adequate transmission of forces according to the resistance mechanism of the pyramid. The lower tension chord consists of a steel box girder with a trapezium-shaped cross-section (*Fig. 4*). The upper compression chord is formed of a series of steel Vierendeel beams, both in the vertical planes (alignments 12, 14, 16, 21, 22', G, H, I, P, Q and R) and in the upper horizontal plane of the roof and in the lower inclined planes. Finally, the inclined planes are conceived as composite structures of steel box-girders and connected slabs made from gluelam timber (*Fig. 4*).

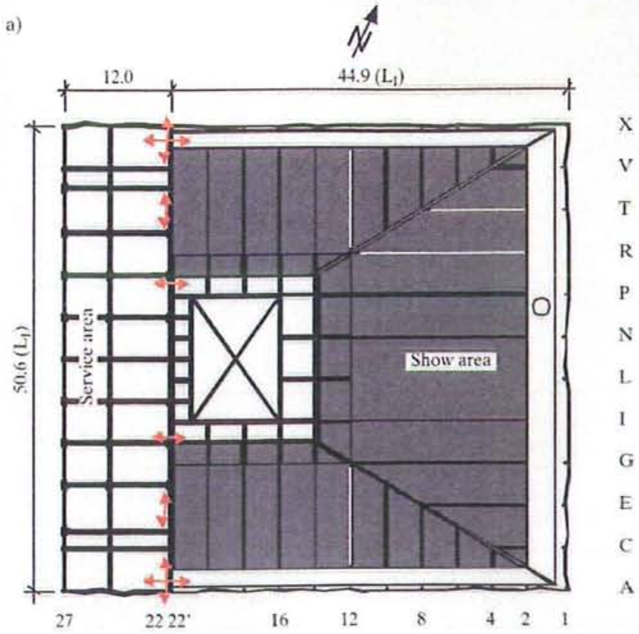
The truncated pyramid is described as false, from the point of view of the mechanism of resistance, since it has only three inclined planes, the functions of the fourth being provided by the service building. To achieve this, the lower chord, the inclined planes at mid-height and the upper chord are connected (at alignment 22') to the service building (*Fig. 2a*). The structure, which is supported by the steel and composite (steel and concrete) pillars surrounding the inner square


a)


b)


c)

*Fig. 1: Finished pavilion; a) Outside view; b) Openings between pillars; c) Interior square*



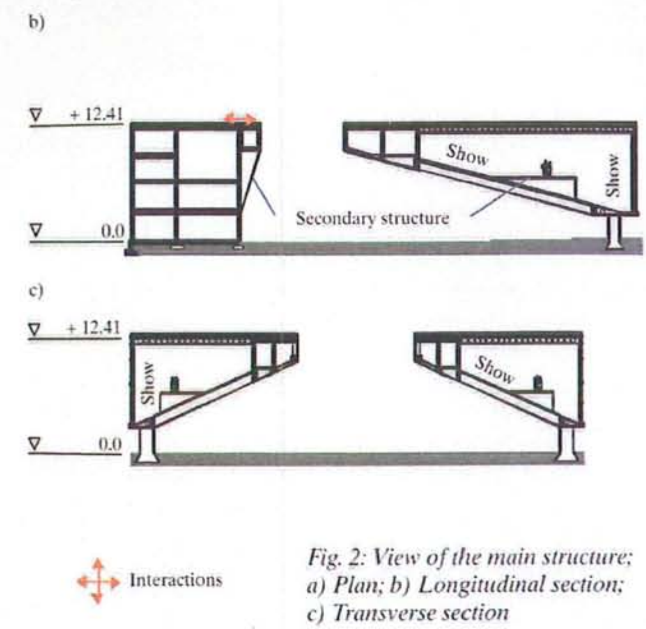




*Fig. 2: View of the main structure; a) Plan; b) Longitudinal section; c) Transverse section*

*Fig. 3: Composite action of prefabricated concrete slabs and steel girders achieved by prestressed bolts*

and resting directly on the ground, has a symmetrical transverse section, but an asymmetrical longitudinal section (*Fig. 2b, c*). The show building is topped by a roof planned as a steel structure that transmits its vertical loads on the one hand to the upper chord of the truncated pyramid and on the other, through the outer façade columns, to the lower chord and thus to the perimetral pillars and to the ground.

The overall stability of the structure is achieved by the false truncated pyramid and its interaction with the service building. In the longitudinal direction of the building, the pyramid is stable in itself, due to the enormous in-plane stiffness of the north and south facing inclined surfaces, constituted by composite steel-timber elements. In its transverse sense, the stability is achieved, by the in-plane stiffness of the inclined surface on the east side and, by the connection (at alignment 22') between the inclined surfaces and the service building (*Fig. 2a*). The connection between the lower chord and the service building is made such that the support reactions of the chord, particularly its horizontal component, are transmitted to the foundations through a bracing system (*Fig. 5b*) integrated in the service building (alignment 22 according to *Fig. 2a*). Finally, the stability of the service building is assured without the need to introduce any additional bracing systems. In the longitudinal direction of the structure, the service building is stabilised, through the connections already mentioned, by the truncated pyramid that is stable in itself. In the transverse direction, stability is achieved through the bracing at axis 22.

An efficient transmission of the longitudinal shear forces between the steel and the timber members of the pyramid can only be reached by means of a glued connection. Such a connection, however, would complicate the dismantling and reassembly of the structure. Mainly for this reason, it was decided not to establish the glued connection for this first and transient use of the building. Steel and timber members should rather be glued together for their reuse as permanent structural elements. Not to establish the composite action also implies a certain increase of deformations. In order to reduce the horizontal deformations of the lower chord – and the subsequent vertical deformations of the upper chord – to acceptable limits, intermediate horizontal supports are added in the axis 8 and 16, roughly coinciding with a third of the span. Each one of these supports is composed of two of the perimetral pillars (composite steel and concrete), forming a frame together with the lower chord of the pyramid and the foundations of the pillars (*Fig. 5a*). To balance the horizontal

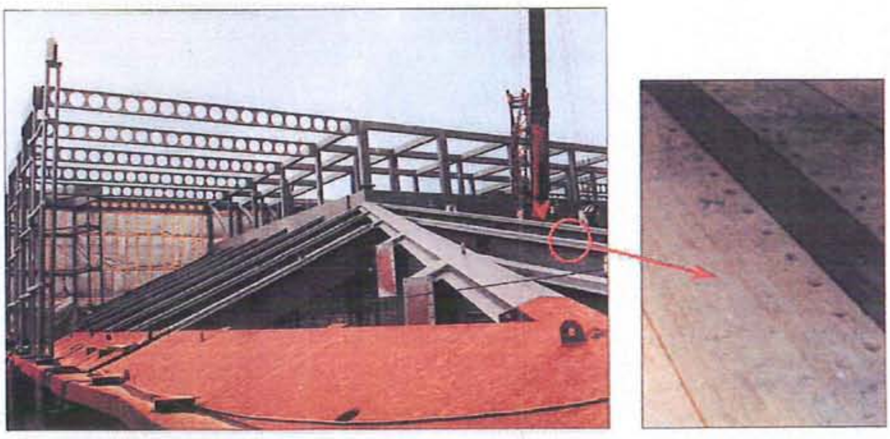


*Fig. 4: Structural elements of the building*

component of the resulting reaction, the two horizontal supports corresponding to each of the two axis mentioned, are joined by means of tension struts, constituted by prestressed cables (two cables for each axis, each made up of 19∅13 mm wires). Ground anchors achieve the stability of each frame. The construction process for the structure determines the type of foundations. During the application of the prestressing force, the upper part, built up on neoprene supports (second stage concrete) can undergo horizontal displacements. After prestressing, the foundation is completed by filling (third stage concrete) the space between the upper and lower parts, to obtain the final static system consisting of a monolithic foundation.

Compared to other possible measures for the stiffening of the structure, for example the introduction of bracings in the inclined planes, the adopted solution with active horizontal supports implies some advantages:

- Deformations due to permanent loads can be compensated by means of the prestressing forces.
- The structural elements can be fabricated without any precamber.
- The structure can be assembled according to its theoretical geometry.

These advantages are important with a view to the reuse of the structure, of which no further details were known at the design stage. The precamber, introduced by the prestressing forces, can easily be adapted to almost any particular conditions (permanent loads) after the change of use.

## Construction

### *Changes to the Original Project*

For different reasons, partly related to the tight construction schedule that did not permit the necessary experimental tests required by German legislation, it was decided to abandon the ground anchors in the horizontal supports for the lower chord. In order to ensure an accurate transmission of the support reactions to the ground without the contribution of the ground anchors, it was necessary to increase the size of the footings considerably, almost tripling the volume of concrete initially planned. However, the concept of the footings in line with the construction process was maintained.

### *Assembly*

After assembling the complete steel structure and mounting the steel sheeting on the roof, the tendons at the axis 8 and 16 could be prestressed. The forces applied released the reactions on the auxiliary structure used to support the upper chord during assembly (*Fig. 6*) and introduced a precamber.

The prestressing forces were determined to compensate deformations due to the self-weight of the structure and 30% (100% according to the original project; the reduction was due to the elimination of the ground anchors and the subsequent stability problems of the foundations) of the other permanent loads. The prestressing forces thus determined were applied in stages. The two tendons at axis 16 were stressed simultaneously, in five steps, up to a total force of 1385 kN. This was repeated for the tendons at axis 8, where the required total force was 930 kN.

### *Measurements*

The effects of the action of prestressing depend on a large number of parameters, some of them associated with important uncertainties: the rigidity of the bolted joints, the interaction between the two buildings, the evaluative stages of the assembly process, the rigidity of the neoprene supports, etc. Because of these uncertainties, it was decided to monitor the structure. The objective of the measurements during the prestressing was twofold. On the one hand, they had to guarantee that the required geometry for the structure was achieved, and, on the other hand, they provided a check that the numerical models used adequately reflected the structural behaviour. This second objective became even more important after the elimination of the ground anchors, originally introduced in order to guarantee the stability of the horizontal supports (*Fig. 5a*). Indeed, the overstressing of the cables could lead to the loss of their stability.

To achieve the mentioned objectives, the following values were measured:

- applied prestressing forces
- horizontal movement of the mobile part of the footings at axis 8 and 16
- vertical deformations of the mobile part of the footings at axis 8 and 16
- vertical deformation of the Vierendeel beams of the upper chord of the pyramid at points 16/I and 16/P
- stresses at different points at the fixed ends of the pillars at axis 8 and 16, and at the upper and lower edge of the inner face of the box girder constituting the lower chord of the pyramid.

At the end of each stage in the application of the prestressing forces, the values measured were compared with the corresponding predicted values. If the difference found was acceptable (the measured values had not to diverge more than 15% from their respective predicted ones), then the process could proceed. If, on the other hand, this limit was exceeded, the process was to be interrupted and the differences analysed. Only if an unequivocal explanation could be found for the divergence, and if the structural safety was guaranteed with adequate probability, could the process resume. In

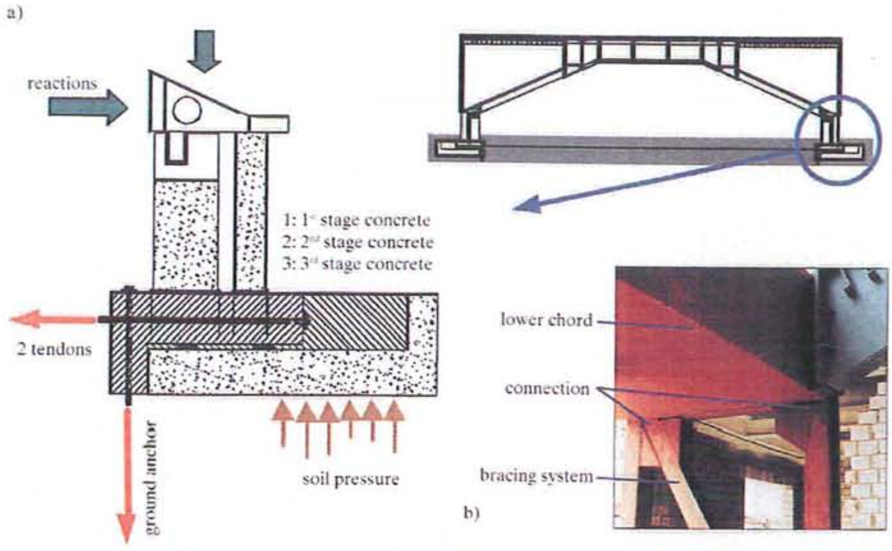



*Fig. 5: a) Intermediate horizontal support for the lower chord; b) Lateral support for the lower chord, constituted by the bracing system of the service building*

*Fig. 6: Upper chord supported on the auxiliary structure during assembly*

fact, an excellent coincidence was observed between the predicted and the measured values, and the process did not have to be interrupted at any time.

## Conclusion

The need for the structure of the Spanish pavilion for the Expo 2000 to be dismountable was the dominant condition for its conceptual design. Very careful planning was required, bearing in mind the complex interactions between the geometry, functionality, structural concept and construction materials used with extensive application of prefabrication techniques. Using a coherent structural concept, in which all the elements contribute to the overall stability of the system, a completely prefabricated and dismountable structure has been achieved. At the same time, the structure has been conceived in such a way that the mechanisms of resistance were unequivocal. A clear identification of the flow of the forces is particularly important with a view to reducing the risks related to dismantling, since loaded elements must be removed and the stability of the continuously altered system is to be guaranteed. At the design stage of the structure, the conditions for its future use were unknown. However, very roughly it can be estimated that the costs for dismantling, transportation and reassembly of the structure most probably would not exceed 70% of the initial manufacture and assembly costs.

**SEI Data Block**

*Owner:*
Sociedad Estatal Hanover 2000

*Architectual design:*
Cruz y Ortiz Arquitectos

*Design assisted by testing:*
Cesma Ingenieros and Institute of Construction Science Eduardo Torroja

*Main Contractor:*
OHL, Hochtief

*Subcontractors:*
Cornils (Steel structure)

Grossmann (Gluelam timber)

| | |
|---|---|
| Steel (t): | 779 |
| Gluelam timber ($m^3$): | 163 |
| Useful area ($m^2$): | 7000 |
| Total cost (USD millions): | 2.83 |
| Service date: | June 2000 |

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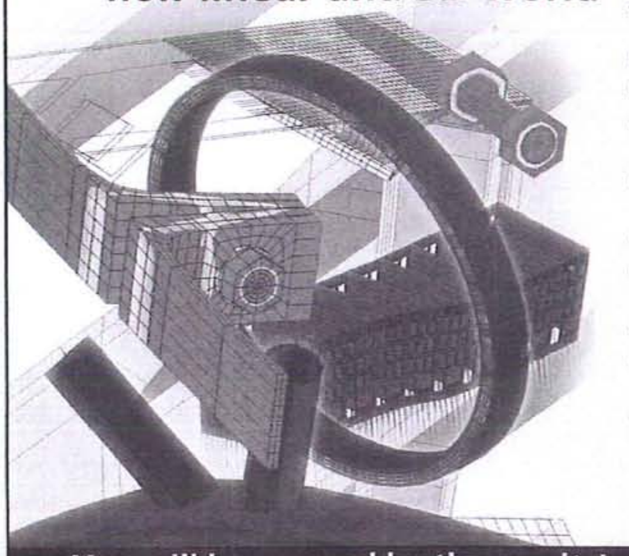

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