Structures in Portugal: An Introduction

Portugal has witnessed, in recent years, the design, construction and rehabilitation of several outstanding structures. Nine of them are presented in this issue of "Structural Engineering International". You are all encouraged to visit them in September 2005, when structural engineers from all over the world gather in Lisbon for the IABSE Symposium on Structures and Extreme Events.

The wisdom of organizing this Symposium on Structures and Extreme Events was most unfortunately confirmed in the Indian Ocean on the 26th of December 2004. Structural engineers understand that structures worldwide may be subjected to extreme events during their design life, which can lead to unforeseen consequences in loss of property and human lives. They know that such situations may be caused by natural disasters and environmental changes, and that they also arise from human errors or man-made events, whether deliberate or involuntary. Notwithstanding, it is still difficult to respond appropriately to these problems, which today remain a kind of "last frontier" in structural engineering.

Portugal has also experienced tragic events. Undoubtedly, the most devastating disaster was the earthquake and tsunami of 1755, affecting Lisbon and the southern parts of the country. Therefore, as we reflect on this extreme event that took place 250 years ago, it is appropriate that Lisbon hold an IABSE Symposium devoted to the discussion of these unforeseen situations that can affect our structures. It is an opportunity to stimulate structural engineers to give more thought to such problems, and to provide information and guidance on how to deal with them.

The Lisbon Symposium is organized by the Portuguese Group of IABSE (APEE) and the National Laboratory for Civil Engineering (LNEC). For more information please visit www.iabse.org/conferences/lisbon2005.

I assure you that you are most welcome in Lisbon and that the Portuguese people will be pleased to share with you their belief in a safer and happier World.

António Adão da Fonseca
Vice-Chair of the Organizing Committee,
IABSE Symposium Lisbon 2005

Casa da Música, Porto

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Introduction

"Casa da Música" is one of those projects in which architecture and engineering are inseparable and strengthen each other. The challenge was to fit a complex functional programme into an object with an unusual form while also ensuring that the support structure should be an integral part of the architect's spatial concept.

For the architect, the elements which engineering needs are opportunities and themes that give form to the space. Making structural sense, columns and sloping walls are formally worked on and integrated into the design, not by disguising them but sometimes by giving them an unexpected leading role. This process creates an initial conceptual freedom which, through strict formal control, leads to the desired result.

The initial idea was for a translucent building with a steel structure. Cost reasons and the loss of the transparency effect, which was the inevitable result of the structural elements' density, led to the choice of white concrete (*Fig. 1*). Although it clearly appealed to the architect, white concrete had not been proposed initially because it is not a common material in Northern European countries where it is difficult to find skilled labour to carry out top quality work in exposed concrete.

The project began in September 1999, following a competition won by the joint-venture of the Office for Metropolitan Architecture and Ove Arup & Partners of which AFAssociados was already a part. The temporary work design and concrete construction phasing was undertaken in 2001 by AFAssociados.

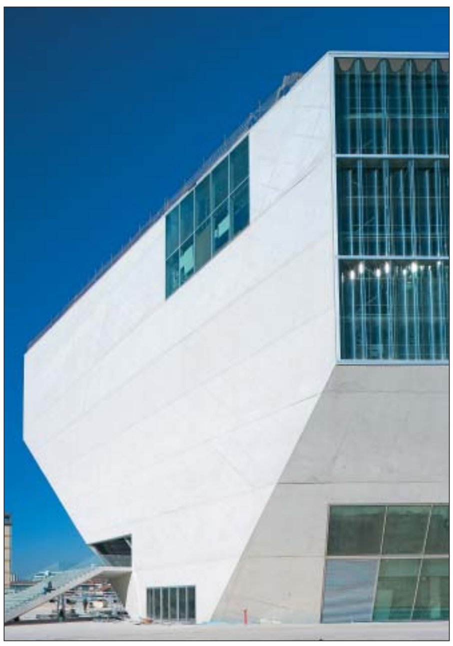

Fig. 1: Southeast elevation – February 2005

In terms of structure, in addition to the need to guarantee the overall stability of the building, the following basic concerns are worthy of mention:

- The need to find a set of structural elements, integrated in the architecture, which ensure that the bearing loads are transmitted to the foundations. The geometrical complexity of the building did not make this an easy task and it was necessary to consider a complex load path, making structural use of most of the concrete walls;
- The need to achieve a strict level of detailing to enable the definition of the building's geometry and structural elements, accurately incorporating all the openings and spaces to be used by the services. Since the building is of exposed white concrete many of the infrastructure elements are embedded in the concrete and the accuracy of detail is thus also applicable to these installations. The reinforced concrete drawings took on the importance of summary drawings and were changed as the result of successive iterations between the architects, structural engineers and services engineers;
- The establishment of a construction scheduling and a support system compatible with the work deadlines and the contractor's preferences;
- The control of surface cracks, due to the importance of this feature for the durability of a white exposed concrete building;
- The guaranteeing that the work carried out would be of excellent quality by making prototypes to allow the testing of materials and work methodologies and to study alternative processes and materials together with the contractor.

General Description

The building houses a 1300 seat main auditorium, rehearsal space and recording studios for the Porto National Orchestra. The main structural elements of the auditorium building are the shell formed by the outside reinforced concrete wall panels 0,40 m thick, and the two large longitudinal walls bounding the main auditorium 1,0 m thick. This major thickness is due to the fact that there are many openings, often large in size, and it is thus important to provide support to perpendicular cantilevering elements.

Considering the shell and its interior, it is found that the centre of gravity is moved to the south of the geometric centre of its base. This fact, and particularly the increase of this eccentricity due to seismic action, led to the use of two inclined columns to give external support at two points located at the intersection of two of its most southern edges with the floor of level 0. These columns pass through the three parking levels and are only visible from there. The unit formed by the external shell, the two longitudinal internal walls, the two external columns and the floor slabs which, acting as membranes, work as stiffening vault ribs for the shell, absorbing and transferring the horizontal forces, form the primary structure and stability system of the building.

The external wall panels of the building act as a three dimensional shell with membrane forces and bending moments. The behaviour of each panel, as a plane stressed structure, contributes decisively to the overall stability of the building. The bending moments result from the action of their self weight and from the loads transmitted by the slabs which are supported on the shell. Sometimes these bending effects would be unacceptable if some auxiliary elements, called "interventions", had not been provided. The major "interventions" are the two large inclined columns which cross the South and North sides and give support to the roof panels (*Fig. 2*).

There are also three circular columns coming from the wall-beams of the small auditorium which support the roof above the South foyer.

Due to the slight slope of the roof panels, certain free edges which were to be very slender would have had excessive deformations if the reinforced concrete shell had not been replaced by steel structures composed of open-web girders or beams in a welded, variable cross section construction (*Fig. 3*). The stiffness of these edges is crucial in the situations where they support the large glass panels.

Fig. 2: Inclined column in South foyer

Fig. 3: East edge of main auditorium roof

North Zone

The extremely complex geometry of the slabs, stairs, ramps and walls on the North side results in several types of structural solutions for supporting the slab loads. In addition to the main auditorium longitudinal North wall and the exterior shell, there are also two elevator shafts and an inclined column, which also act as vertical support elements. When possible, the slabs are directly supported on the vertical elements or on the exterior shell. In the areas where this is not possible, the slabs are supported on beams or wall-beams which are sometimes also supported by other wall-beams (*Fig. 4*).

South Zone – Foyer

On the South side there is the large volume of the main entrance gallery which is interrupted at its upper part by the small auditorium. Between this gallery and the main auditorium South longitudinal wall there is a 7 m wide zone for vertical and horizontal circu-

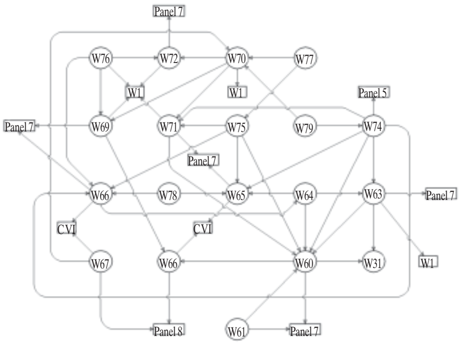

Fig. 4: Load path on North side structural elements

lation and service areas. This strip is bounded to the South by a 0,35 m thick reinforced concrete wall with a large number of major openings.

The vertical supports for the South side slabs, which in the gallery zone are between the foundations and the main access stair level and in the referred circulation zone up to the roof, is provided by the exterior shell, the main auditorium South longitudinal wall, the referred 0,35 m thick wall and also the South inclined column which intersects the gallery space.

At a higher level spanning over the space between the exterior shell and the South longitudinal wall, is the small auditorium. Its main structural elements are two wall-beams 0,45 m thick and variable height. The small auditorium ceiling and floor layers are composite slabs supported on steel beams (*Fig. 2*).

Main Auditorium

The acoustic isolation of the main auditorium is assured by separating the auditorium structure from the rest of the building. This separation is referred to as being a “box in a box” (*Fig. 5*). In this separation the “inner box” floor, walls and ceiling only come into contact with the building’s structure through resilient supports.

Fig. 5: “Inner box” under construction

For acoustic reasons each of the main auditorium extreme windows is made of two glass walls 6,5 m apart. These windows are 23,2 m wide and approximately 14 m high. The glass walls consist of three stacked panels in an “s” shape. The upper two are suspended from the roof while the lower one is supported on the base. Wind load resistance is achieved by the wavy glass section spanning between two discreet horizontal trusses, located at the lower and upper thirds of the height between the two glass planes (*Fig. 6*).

Fig. 6: Main auditorium West window

Auditorium Roof

The slab above the main auditorium (level 8) spans the 24,2 m space between the main longitudinal walls. For this slab, two structurally distinct systems were adopted:

In the restaurant area, where between this slab and the roof there is sufficient height, there is a solid slab supported on the lower flange of steel trusses spaced 6 m apart. These steel trusses go up to the roof and have different geometries imposed by the irregular form of the roof (*Fig. 7*). These trusses also give support to the roof panels of the exterior shell.

Fig. 7: Steel trusses in restaurant area

In the rest of the area, there is a composite steel-concrete slab, 0,20 m thick, supported by built-up welded steel beams with 1,9 m height and spaced 3 m apart. These beams have openings in their webs to allow the passage of the technical installation pipes (*Fig. 3*).

Parking Garage

The parking garage floors are solid reinforced concrete slabs. They are supported on isolated columns, on reinforced concrete walls, on the sloped walls of the auditorium building, and on the peripheral retaining walls. The

Fig. 8: General view of the parking garage

columns are circular with truncated conical shear heads and are generally set out in a 7,8 m by 7,8 m grid (*Fig. 8*).

White Concrete

It should be highlighted that this is a building made of white concrete which is, to a large extent, exposed. The concrete is simultaneously the structure and the final finishing of the building. This fact makes particularly important the verification of serviceability limit states. So, the good appearance of exposed white concrete is guaranteed by controlling crack widths and by ensuring that forces are correctly quantified.

The correct specification of the concrete is particularly important and great care must be taken in the placing of formwork and steel reinforcement with the site always being kept clean and the workers always concentrating fully on their work.

The concrete is of European grade C40/50 (characteristic strength: 40 MPa cylinder, 50 MPa cube), with a minimum cement content of 380 kg/m^3 of 42,5 class white BR I cement, coarse calcareous inert materials, fine calcareous and granite sands and a very fine grained calcareous filler. It is the presence of the granite sand that makes the colour of the concrete slightly greyish and not yellowish as often happens when concrete is made as “white” as possible.

From previous experiences it was known that it was normally good practice to remove formwork very quickly from the white concrete’s surfaces to avoid the appearance of marks and blemishes. The impossibility of being able to do this with some panels, due to the complex formwork system, raised the question of the risk of appearance of such marks, naturally undesirable, and it was necessary to make a choice; either the marks should be accepted or an even more sophisticated formwork system should be used. The timely use of a prototype showed the route to be followed since this indicated that the marks disappeared as the concrete aged. Several tests were undertaken on parts of the building which confirmed this behaviour and it was thus accepted that the formwork could be kept on for a greater length of time.

Dirt stains and oxidation drip marks, which could not be avoided, were removed by a final cleaning with appropriate chemical products chosen after several tests. Finally, the entire exterior surface of the concrete was protected with a water-repellent product to avoid the appearance of fungi, a particular risk on the north-facing surfaces.

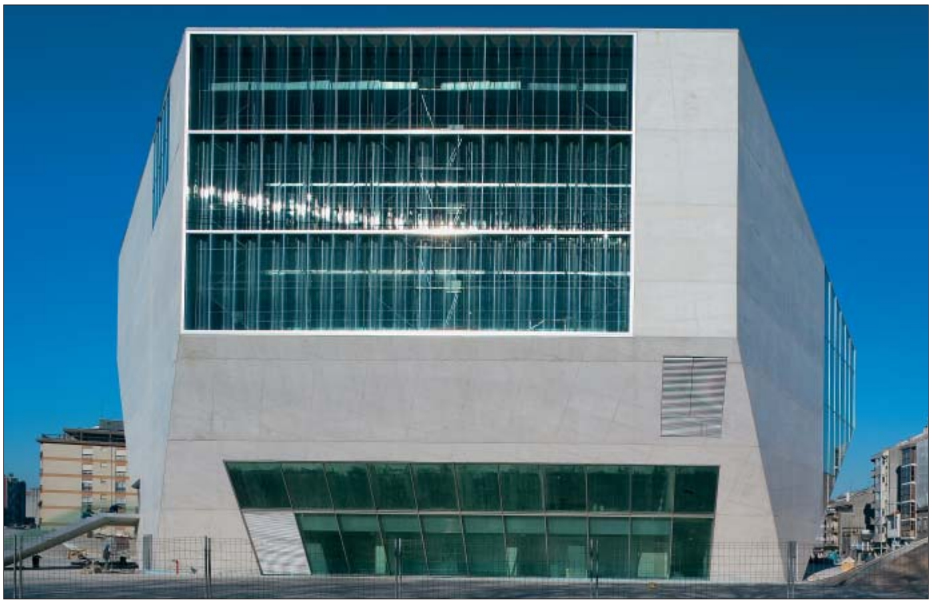

Fig. 12: East elevation – February 2005

Calculations and Detailing

The overall analysis of the auditorium building was carried out using a three dimensional shell finite element model. The model is composed of all the elements which form the primary structure (*Fig. 9*). It was used to determine the forces acting on all the elements due to gravity, thermal, shrinkage, seismic and wind actions, and later the model was also used to determine displacements and deformations.

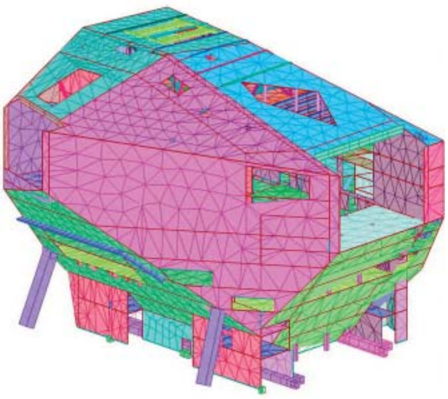

Fig. 9: Finite element model

Construction Phasing

The constructability of the auditorium building of the "Casa da Música" was one of the main challenges facing the entire team involved in the project and construction. The stability of the sloped walls during construction and the fact that the structure would only be stable as a unit, after the conclusion of the entire exterior shell, required a specific study for the phasing of the construction of the structure (*Figs. 10, 11, 12*).

The study of construction phasing carried out had the additional objective of minimising the time that formwork and its temporary structures remained in place in order to free up the underlying areas and to carry out other necessary finishing work (*Fig. 12*). Accordingly, based on the contractor's initial work plan, which defined the sequence of concreting, 88 construction phases were defined for the building and the stability of all these phases was studied individually.

Fig. 10: Construction work – May 2002

Fig. 11: Construction work – May 2003

Foundations

For the auditorium building, indirect foundations of piles sunk in slightly altered granite were used. In the garage, footings based in the gravelly layer present at the column base level were used.

Conclusions

The construction of the "Casa da Música" was a great challenge for the entire team involved in the project. Design architects and engineers worked closely together for 6 years to make the construction of this building possible and to ensure that it will become a landmark of Porto. The success of the project would not have been complete without the great work done by all contractor engineers and site workers.

SEI Data Block

Owner:
Casa da Música / Porto 2001, SA, Porto, Portugal

Architect:
OMA / Rem Koolhas, Rotterdam, The Netherlands

Structural design:
Ove Arup & Partners, London, UK
AFAssociados, SA, Porto, Portugal

Contractors:
Somague / A. M. Mesquita, Portugal

Reinforcement steel (t):	5000
Construction steel (t):	600
Concrete (m^3):	35 000
Total cost (EUR millions):	60
Service date:	April 2005