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Response of the building "Mercado Torroja" of Algeciras, under seismic load

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Abstract

The Market of Algeciras is one of the most singular buildings of the Spanish engineer Eduardo Torroja. The roof of this structure is a spherical shell supported on eight peripheral piles. This building was built in 1933, and it is being restored at the present. This paper studies the behaviour of this structure when an earthquake hits it. The analysis is made using the current techniques of finite elements [4]. Since there was no regulation when the structure was built, the norm NCSE-94 [6] has been used in the analysis.

1 Introduction

The work of the Engineer Eduardo Torroja, (1900-1961) is considered world-wide as one of the most important works for the progress of Civil Engineering. One of his singular works is the market of the town of Algeciras. This building is composed of a reduced spherical shell made of armed concrete and supported on eight columns which are the vertices of a regular octagon, figure 1.

The main element is the spherical dome that constitutes the roof of the structure. This shell has a diameter of 47.80 m and a radius of curvature of 44.10 m. Its thickness decreases progressively from 50 cm at the supports to 9 cm at the

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highest point. Considering that the shell is made of armed concrete, a thickness of 9 cm is worthy of admiration even nowadays. The forces are led to the supports by intersections of the dome with cylindrical vaults that start at the supports. Pre-stressed concrete is also used in an ingenious system of bars. Once the pre-stress step is concluded, the system is filled with concrete to avoid problems of corrosion, figure 1.

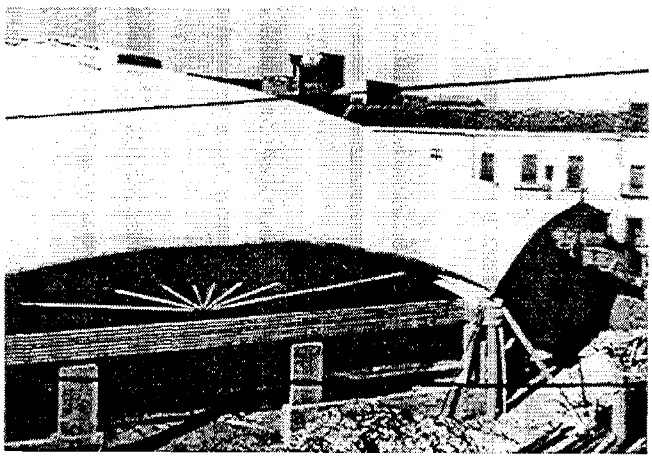

Figure 1. Picture of the dome during the construction of the building

Torroja used the calculation methods available al that time, that is, the analytical methods derived from the differential equations of spherical shell [2][3]. Due to the special characteristics of parts of the structure, a model on scale was also used. It can be said that he used the analytical method and the model on scaled as an analogical computer. Figure 2.

If Eduardo Torroja had carried out his work at the present time, he would surely have used a digital computer with a program based on the Finite Elements Method [4] or the Boundary Elements Method. This paper tries to show the likely process Torroja would have followed.

A virtual model has been built instead of the one on scale used by Torroja. Then, different tests can be performed. The seismic response of the building is presented in this paper as a first approach.

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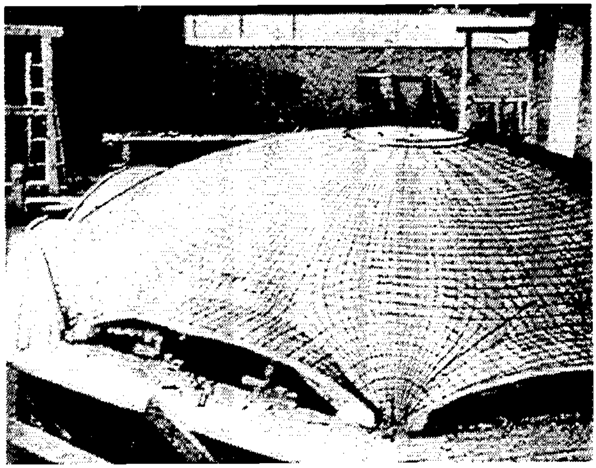

Figure 2: Model on scale of the dome of the market

The results obtained show that, from the static point of view, the design made by Torroja was correct. However, they also show that this singular building could have serious problems when reached by an earthquake corresponding to its location.

This building was constructed in 1933, when there was no seismic regulation in Spain. The first norm that takes the seismic response into account was the MV-101 from 1962. It is then necessary to study the behaviour of this building when reached by an earthquake and if it follows the current Spanish seismic regulation (NCSE-94). This way appropriate measures can be inferred in order to avoid the collapse of the building.

2 Model

A model has been developed using the technique of Finite Elements [4], as it can seen in figure 3. The commercial software ANSYS [1] has been used. With this method displacements in the nodes can be obtained. From them, deformations and forces are derived.

The discretization has been carried out using a shell element of 8 nodes, called 'shell93' [1]. This element has the following characteristics:

The element is defined as a quadrilateral or triangle in three dimensions. It can have a different thickness in each node. It has six degrees of freedom in each node: lineal displacement in the three direction of the nodal system of reference and the corresponding rotations in the axes. The form functions are quadratic in

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the two direction of the plane, so that good adaptation to the curved shell can be achieved.

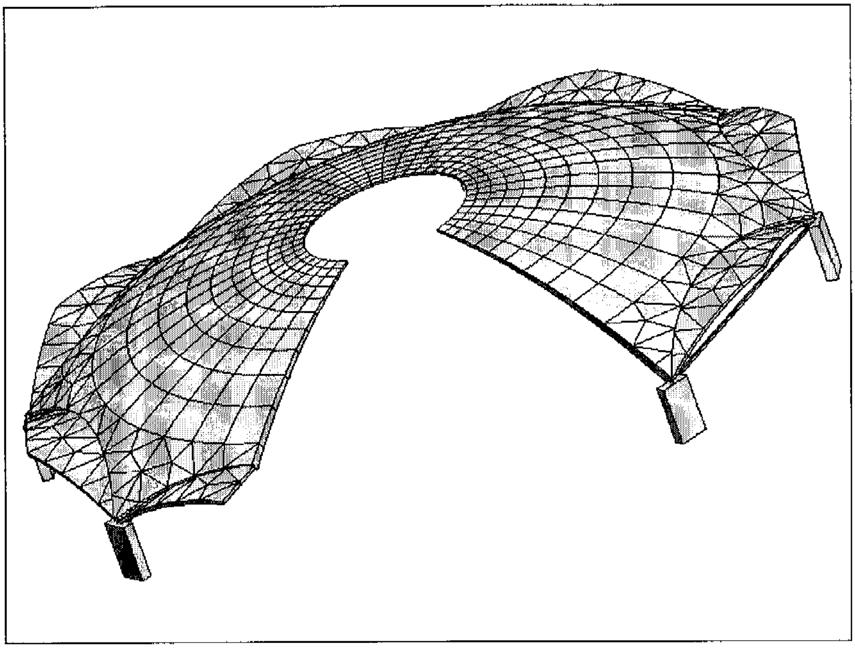

Figure 3: Model of finite elements

The results provided by the model are the following:

a) Nodal displacements.
b) Membrane forces in the plane of the element, bending moments referred to the local axes X and Y in the plane of the element, and shear forces normal to the plane of the element.

The material used to construct the building was reinforced concrete. Both its making process and use in construction were worse then those achieved nowadays. Considering these limitations and not knowing the tests made by Torroja, the worst concrete considered in the current norm EHE-98 [7] is used in the model. Its characteristic resistance is 20 N/mm^2.

The load due to its own weight has been taken as the most important, since it is of the order of 350 Kg/m^2. No other loads have been considered in the static analysis.

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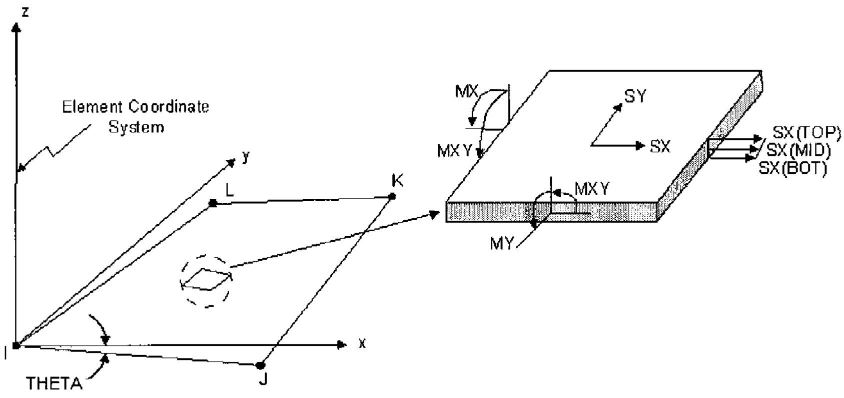

Figure 4: Shell type element

The boundary conditions corresponding to the supports are the following: they are taken as articulated supports between the shell and the columns, because of the reinforced configuration of the columns. Rotations and displacement at the base of the columns are not allowed, figure 5.

These columns are mainly subjected to compression forces under static loads, since there is a closing ring that gives rigidity in the radial direction. This is obtained with an interesting post-stressed system, figure 1.

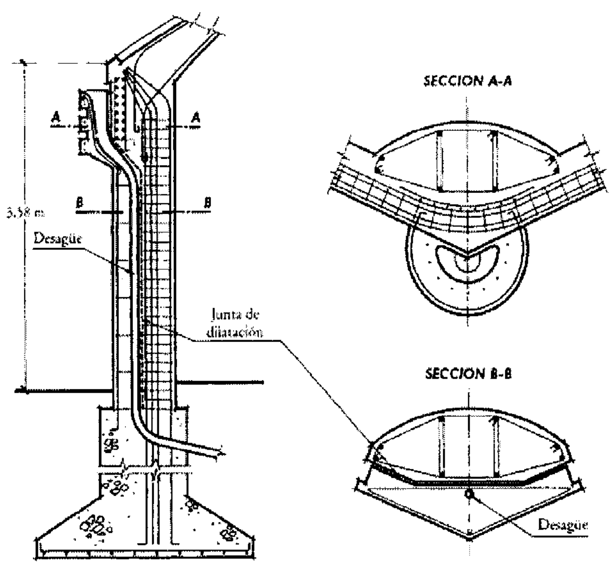

Figure 5: Columns of support of the dome

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3 Analysis performed

The following analyses were performed:

a) Static dead loads
b) Eigenvalue
c) Spectral response

In all cases, various forms of the fundamental equation of motion were used:

$$[M]\mathbf{x} + [C]\mathbf{x} + [K]\mathbf{x} = \mathbf{f}$$

where $[M]$= mass matrix. $[C]$= damping matrix.$[K]$= stiffness matrix. $\mathbf{f}$ = force vector. $\ddot{\mathbf{x}}, \dot{\mathbf{x}}, \mathbf{x}$ = acceleration, velocity, and displacement vectors, respectively.

3.1 Static dead load analysis

A simple dead load analysis was carried out to obtain the static forces, displacements and strains. For the static analysis, the fundamental equation of motion reduces to:

$$[K]\mathbf{x} = \mathbf{f}$$

for $\ddot{\mathbf{x}} = \dot{\mathbf{x}} = 0$.

This analysis was carried out to evaluate the approximation rate achieved with the initial design and to detect possible crack problems.

3.2 Eigenvalue analysis

This analysis was performed to determine the frequencies of the structure. For the case of a system in free vibration, without damping, the equation of motion reduces to:

$$[M]\mathbf{x} + [K]\mathbf{x} = 0$$

This can be represented by the characteristic equation:

$$([K] - \omega^2[M])\mathbf{x} = 0$$

which it is true if the following condition is satisfied

$$\det\left|\left([K]-\omega^2[M]\right)\mathbf{x}\right|=0$$

Solutions to the above equation, give the natural frequencies, as well as the modal vectors.

3.3 Response spectrum analysis

To evaluate the behaviour of the structure in case of earthquakes, an analysis of spectral response has been carried out. The corresponding curve was obtained from the standard NCSE-94, considering a loose granular soil, of type III, with coefficient C = 1.8.

The basic seismic acceleration for Algeciras is a_b=0.04 g, and the contribution coefficient K=1.3. The acceleration for calculus is $a_c=\rho a_b$, where ρ= 1.3 for being a construction of special importance.

The spectrum of the elastic response, according to the standard norm can be seen in figure 6.

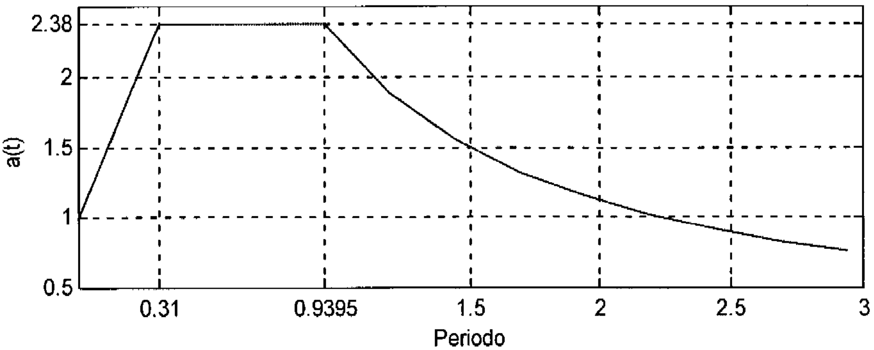

Figure 6: Spectrum of elastic response

The modal combination method used by the standard is the square root of the sum of the square displacements (SRSS).

$$u_{j,\max}=\sqrt{\sum_{i=1}^{n}u_{ij,\max}^2}$$

4. Results

4.1 Static dead load analysis

The static analysis [5] was carried out to verify the level of forces in the structure and to have some reference values which the results of he dynamic study could be compared with. The forces have been calculated in an spherical reference system where the coordinates X and Y indicate the direction of the parallels and the meridians respectively. TX and TY forces contained in the surface of the shell are shown in figures 7 and 8. Bending moments MX and MY are also shown.

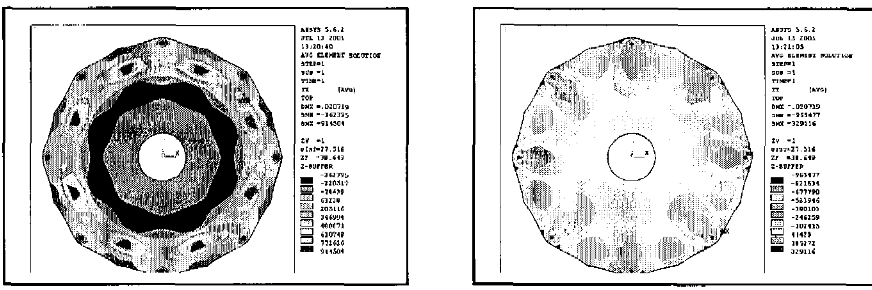

Figure 7: Forces TX and TY

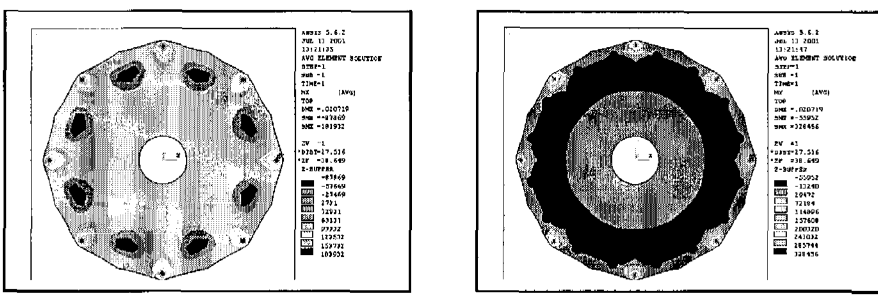

Figure 8: Moment MX and MY

The compression forces and the moments that take place at the base of the columns under static dead loads, can be seen in table 1:

Table 1: Static forces at the base of the columns

COLUMN	AXIAL F. (KN)	MOMENT Y (kNm)	MOMENT Z (kNm)
ALL	-1514.7	261.4	0

4.2 Eigenvalue analysis

The modal analysis was carried out extracting the first 4 modes which are shown in figure 9.

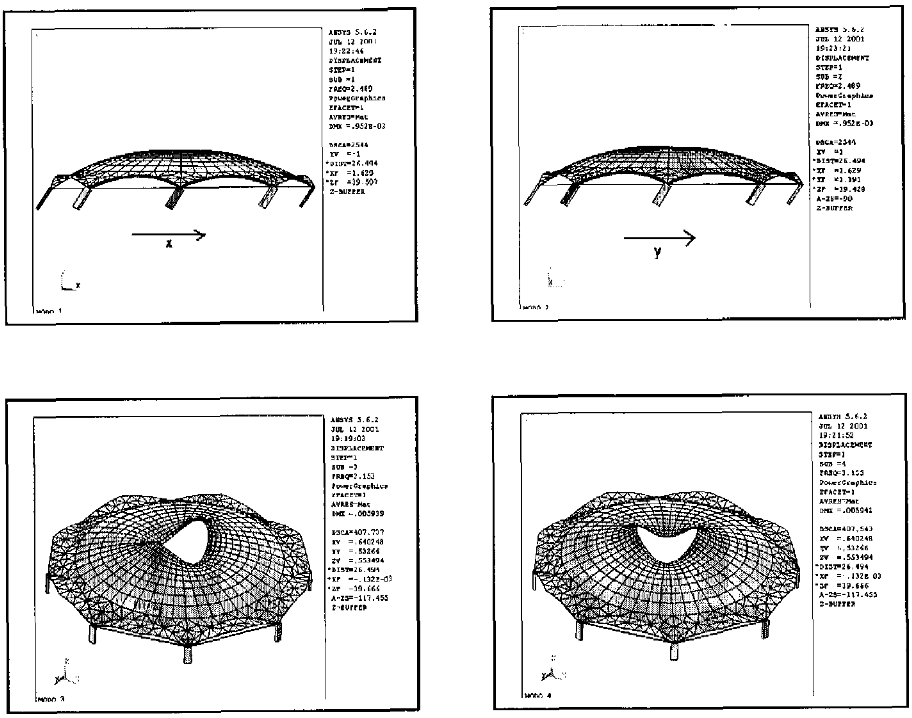

Figure 9: First four mode shapes.

The eigenfrequencies are:

$$f_1 = 2.409 \text{ Hz} \quad f_2 = 2.409 \text{ Hz} \quad f_3 = 3.153 \text{ Hz} \quad f_4 = 3.153 \text{ Hz}$$

Double frequencies take place due to the symmetry of the building.

4.3 Response spectrum analysis

The forces obtained by the modal combination can be seen in the figures 10 and 11. The orientation of these forces are the same as those obtained in the static analysis.

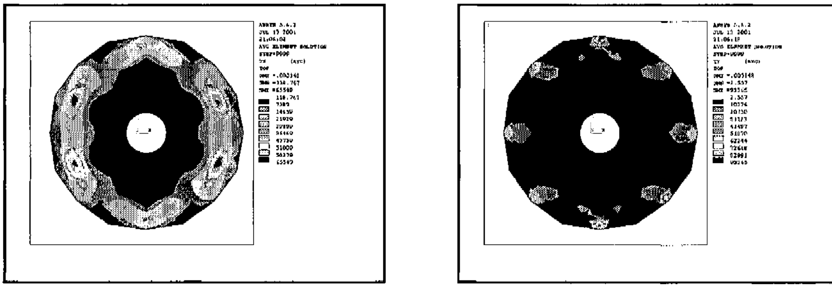

Figure 10: Forces TX and TY

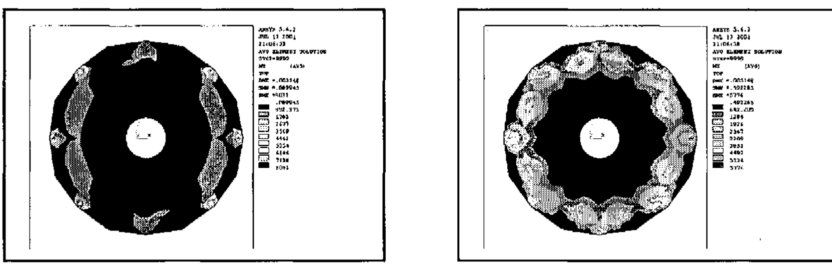

Figure 11: Moments MX and MY

The traction forces and the moments that take place at the base of the columns under dynamic solicitation can be observed in table 2.

Table 2: Dynamic forces at the base of the columns

COLUMN	AXIAL F. (kN)	MOMENT Y (kNm)	MOMENT Z (kNm)
I,V	50.48	147.14	89.22
II,V1	33.79	98.53	861.42
III,VII	3.91	11.38	1153.7
IV,VIII	37.68	109.86	772.61

Combining the results from the static and dynamic analysis at the base of the columns the maximum forces can be obtained, so that the failure of these elements can be studied under bending and compression. Elements subjected to the same forces are grouped in pairs in table 3.

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Table 3: Combined efforts

COLUMN	AXIAL F. (kN)	MOMENT Y (kNm)	MOMENT Z (kNm)
I,V	-1464.243	408.360	89.215
II,VI	-1480.907	359.843	861.420
III,VII	-1510.707	272.741	1153.700
IV,VIII	-1476.924	371.130	772.610

A calculation considering the current norm on concrete (EHE) gives the following graphs which represent both the moments and the axial forces on the columns. The results for the column under static load only is shown in the first graph . The second one shows one of the less loaded columns subjected to static and dynamic load, figure 12. The rest of the columns have a similar and more enhanced behaviour. Bars with a diameter of 20 mm have been estimated from data used in figure 5 and the minimum resistances under the standard have been used for the concrete.

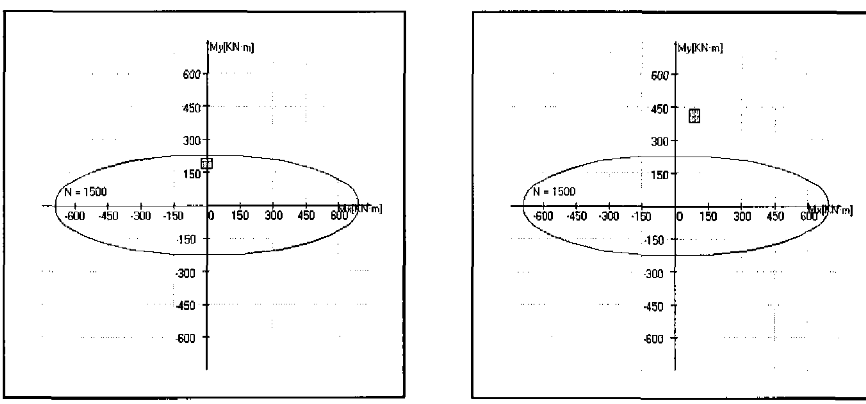

Figure 12: Diagrams of maximum forces in base of columns, and state of the columns I and V, for the static case and for the dynamic case

It can be seen that the combination of forces leads to critical situations in the columns. Once the real data for the sections of the reinforce bars are used, this problem will be confirmed.

5 Conclusions

The static and dynamic behaviour of the Market of Algeciras has been studied using the modern numerical methods. The following conclusions have been obtained:

a) The deformations and the static forces are in agreement with the shell theory.

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b) The dynamic effects of an earthquake on the building are important, specially at the base of the columns, according to the standard NCSE-94.

Future developments of this work are the following:

a) Improvement of the geometry of the model and use of the real data of the reinforce bars.
b) The soil - structure interaction will be considered.
c) Non linear time analysis.
d) Design of a system that avoids the destruction of the building when reached by an earthquake.

Acknowledgements

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