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Materials Modelling and Modal Analysis of the Lighthouse in the Venetian Harbour of Chania

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Structural behaviour in general and modal response in particular are of major importance for the strength evaluation and the aseismic design of buildings. Both are influenced by the material behaviour and assumptions regarding the foundation of the structure. The latter factors are not in general known for monuments and a combined experimental study and parametric computer modelling must be performed for their evaluation. These aspects are discussed here with reference to a masonry lighthouse in the venetian harbour of Chania.

1 Introduction

For the strength evaluation and the aseismic analysis of structures the modal analysis method is widely used. It combines the high capacity of the computational mechanics methods, which can be used for the structural analysis modelling, with the statistical nature of the earthquake loading (cf. Naeim, 1989; Eurocode No8, 1993). The structural behaviour of the material and the conditions of the foundation in masonry structures is not known and must be estimated. This is due to the high inhomogeneity of the structure (for instance stones, mortar, interfaces, unknown faults etc.) and the lack, in most cases, of a reliable quality control during their construction. The reliability of the structural analysis modelling and our ability to perform strength analysis and restoration studies depend on the reliability of the adopted material model. Therefore, a combined experimental study with a parametric computer modelling, assisted by a historical survey and a site investigation is used for this purpose. The material constants are obtained from tests of specimens taken from the structure. In situ modal testing of the whole structure on the other hand gives its dynamic behaviour (eigenmodes, damping), and provides both structural and material modelling. The historical and site investigation give additional clues for the structural model and the need for consideration of additional variables in the study, like the existence of damaged zones, or areas with different materials or different structural elements. A parametric computer investigation adjusts the parameters of a chosen structural analysis model to include all the above mentioned variations of data.

The effect of some parameters related to the material on the modal analysis of a masonry lighthouse in the venetian harbour of Chania is discussed here. The effect of the assumptions for the base of the lighthouse and the attempts to represent a damaged zone on the body of the tower are discussed in this work. More details on the finite element modelling of the structure and the application of the modal response method on monuments can be found in Stavroulaki and Leftheris (1995). The application of the modal test method for historical buildings is also described in Leftheris et al. (1995).

2 Structural Modelling

The lighthouse in the Venetian Harbour of Chania is a masonry structure which has been constructed by Egyptians in 1838. It consists of the base and the cylindrical tower, with heights equal to seven and eighteen meters, respectively. The thickness of the wall is about 0.8 meters.

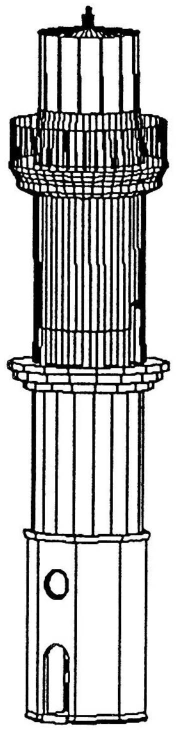

Figure 1. CAD Geometry Model of Lighthouse

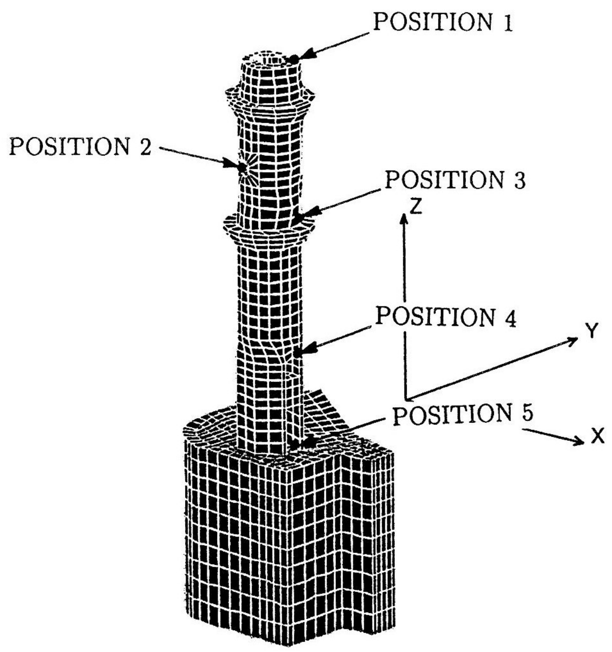

Figure 2. Finite Element Model with the Base
The symbols (•) indicate the five positions of accelerometers

A detailed geometrical model of the structure was extracted in suitable 3-D programmes of geometric modelling (Autocad, Release 12) (Figure 1). After that a finite element discretization of the structure (solid modelling) was constructed by choosing the appropriate elements for the meshing and the modelling of the mechanical behaviour of the structure. The finite element structural analysis method was used (Figure 2). This step can in principle be done automatically in simple structures. In the case of the lighthouse several interventions by the investigators were required in order to avoid the automatic generation of a finite element model which is unwieldy and sensitive to numerical errors. In the final discretization all the necessary controls were done (for example the relationship between the dimensions of the elements and the angles of them must lie in acceptable ranges) in order to avoid numerical errors and to increase the reliability of the model.

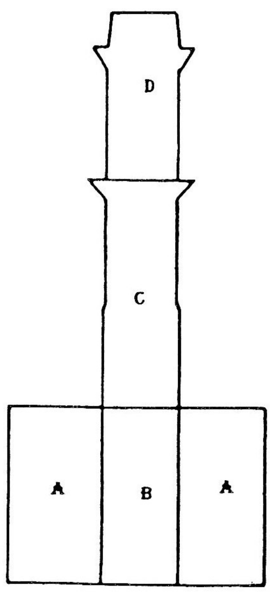

Figure 3. The Parts of the Finite Element Model

The finite element model of the lighthouse as shown in Figure 2 is composed from the following parts (Figure 3):

Part A represents the perimetric base.

Part B represents the section of the body of the lighthouse which continues through the basis to the foundation.

Part C represents the first and the second cornice together, and

Part D represents the third cornice, the upper part, and the section of lighthouse with the slope.

The most important problems that appeared in the modelling were in the regions of the cylinders where the geometry changes and in the regions of the cornice. In these areas important interventions by the investigators were required in order to allow for small deviations from the actual geometry. Some parts of the structure like the architectural details that have no significant participation in the structural behaviour, and some parts that are not critical for the resistance of the structure were not included in the model (e.g. the metallic cover with the glass panels which is on the top of the lighthouse and protect the electrical equipment and the light). However critical characteristics of the lighthouse like the slope of the upper part were taken into account. The slope of the last part of the lighthouse induces additional bending moments even under static loads due to its structural weight. From the historical survey it has been found that this slope was caused by a strong earthquake which took place at the beginning of this century. In the modelling of the base of the lighthouse the parapet which exists on its crowning was included as a concentrated load, because it does not affect the resistance of the main body of the lighthouse and the base. In fact the incorporation of this flexible parapet on the top of the monument (see Figure 1) in a preliminary investigation led to localized vibration modes which do not influence the mechanical response of the main structure. The existence of steel reinforcing rings on the main body of the lighthouse was included indirectly in the model and particularly in the constitutive law of the material. The steel rings are activated indirectly by lateral expansion (Poisson effect) of the masonry, which, since it has essentially no mortar, has theoretically zero resistance in tension. This simplification permits us to use linear elastic analysis. Strength criteria were used in the form of allowable stresses.

We used hexahedral solid elements which are suitable for both linear elastic analysis and non-linear inelastic analysis. They have eight corners, eight nodes and three displacement degrees of freedom for each node.

3 Modal Testing

In order to determine the reliability of the structural analysis modelling and the assumed material model, in situ measurements were carried out. The knowledge of the dynamic characteristics of the structure leads to the prediction of its response under an existing seismic vibration. This knowledge is the basis of an aseismic design.

A series of 10 measurements of ambient and hammer blow vibrations were carried out. The four accelerometers of each series were placed at different places. In Figure 2 the positions of the four accelerometers can be seen. These are, one on the top of the lighthouse, one in the base, one in the foundation and the last one in the base of the first cornice with the slope. The different arrangment of these positions gave us different series of measurements.

A digital accelerograph with four solid state accelerometers of high sensitivity, a portable computer and special programs related with the collection, recording and postprocessing of the recorded data were used.

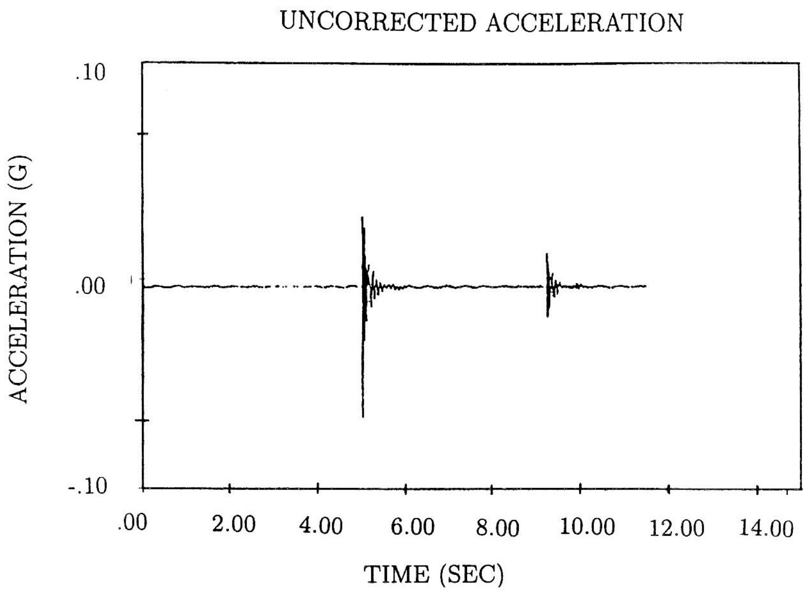

Figure 4. Recorded Acceleration vs. Time

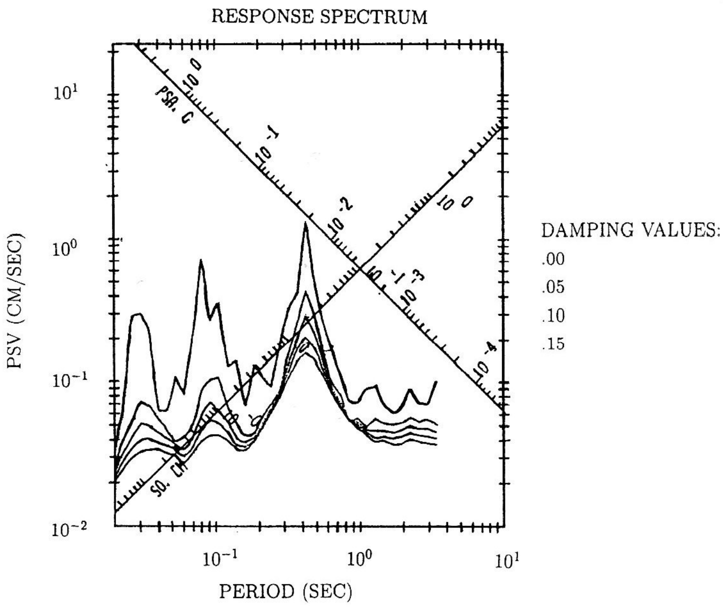

Figure 5. Response Spectrum of a Point on the Top of the Lighthouse

The low amplitude dynamic lighthouse response was recorded in the form of acceleration versus time (cf. Hudson, 1979). Further analysis of these data using Fourier transform and filtering was utilized for the identification of the natural frequencies and the modes of the structure (cf. Trifunac, 1971-1974).

The main frequencies obtained were 2.2, 6.23, 10.17 and 11.7 Hz. The corresponding periods can be seen in Table 2 with shaded numbers. It can be seen in the same table that they compare well with the results of the structural analysis models.

During the execution of the in situ testing we encountered difficulties in placing accelerometers in appropriate positions. Specifically, points on the second cornice were not accessible since no window exists in this part where we could place an accelerometer. The same was true with the points on the stairs inside. The flexibility of the steps and the unknown actual state of their joint to the main body of the lighthouse could create unpredictable faults in the measurements. Another difficulty we faced was the unknown materials inside the core of the foundation and the base.

These difficulties could create problems of identification of the dynamic characteristics of the lighthouse. With the parametric computer investigation, however, we were able to overcome them. So in Table 2, it is shown that the periods that were extracted from the in situ testing correspond with those of the different structural models. These results gave us the particular characteristics of the lighthouse, that correspond with the materials and the method of construction.

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4 Material Assumptions

Without adequate data concerning the construction of the foundation it was necessary to consider different models with various assumptions. A linear elastic material was used for modelling the material structure. Test results of the strength of the stone were used. Based on Figure 3 the models that we examined were the following:

I. The model without the base

In this case we considered the base as rigid so that parts A and B are not involved. Parts C and D are modelled with 2564 nodes, a total number of 7692 d.o.f. (3-D model) and 1604 3-D elements. Both parts C and D consist of the same material.

II. The model with the soft base

The model was composed from the parts A, B, C, D with 5491 nodes, a total number of 19083 d.o.f. and 4015 3-D elements. We considered different materials for the base (parts A and B) and for the main body of the lighthouse (parts C and D).

III. The model with soft base and extended body

Here we considered that the body of the lighthouse continues through the base to the foundation. Parts B, C and D have the same material different to part A. This model consists of 5491 nodes, a total number of 19083 d.o.f. and 4015 3-D elements.

IV. The model with a very soft base

In this case we considered that part A does not exist and the model is constructed from the parts B, C and D with 3269 nodes with a total number of 9633 d.o.f. and 2195 3-D elements. Parts B, C and D have identical material.

V. The model with a soft cracked zone

Finally we examined a model with the same element grid as for model II. Parts C and B have the same material, a different material was assumed for part A. We also considered a new material for part D, the upper part of the lighthouse. In this part we included the slope with a soft cracked material i.e. a material with a low modulus of elasticity.

By using simplified assumptions for the macroscopic modelling of masonry structures, see Tassios (1987), the following material constants were chosen: The modulus of elasticity for each model that we examined is given in Table 1. A Possion's ratio $\nu = 0.15$ is considered throughout and material density p = 1944 kg/m^3 for the main body of the lighthouse and p = 1700 kg/m^3 for the base.

5 Modal Analysis Results

In order to evaluate the behaviour of the structure under seismic excitations it was necessary to calculate the dynamic characteristics of the selected models. This meant the calculation of the natural frequencies to establish the modes of the models and to select that ones that contribute significantly to the vibrations of the structure under earthquake excitation. So, the eigenproblem was solved by the Lanczos method which is considered to be one of the best available methods for large scale structures (cf. Bathe, 1984). The calculated periods for the five models described above are given in Table 2. In addition some characteristic eigenmodes for the examined models are given in Figure 6.

Model \ Part	A	B	C	D
I	0	0	8825 x 10^5	8825 x 10^5
II	6150 x 10^5	6150 x 10^5	8825 x 10^5	8825 x 10^5
III	6150 x 10^5	8825 x 10^5	8825 x 10^5	8825 x 10^5
IV	0	8825 x 10^5	8825 x 10^5	8825 x 10^5
V	6150 x 10^5	8825 x 10^5	8825 x 10^5	8825 x 10^5

Table 1. Modulus of Elasticity in kg/m², for the Parts of the Examined Models

Modes \ Model	I	II	III	IV	V
1	0.9387	1.0873	1.0728	1.7855	2.1720
2	0.8864	1.0190	1.0050	1.7510	2.1277
3	0.18180	0.2040	0.2027	0.3309	0.8259
4	0.1727	0.1899	0.1887	0.3122	0.6214
5	**0.1667*** (0.1605)	0.1814	0.1805	0.3101	0.5976
6	**0.1636*** (0.1605)	0.1210	0.1188	0.2509	**0.4627*** (0.4545)
7	**0.1026*** (0.0983)	0.1120	0.1109	0.1407	0.3521
8	0.0716	**0.1011*** (0.0983)	**0.1003*** (0.0983)	0.1256	0.3278
9	0.0672	**0.0845*** (0.0855)	**0.0841*** (0.0855)	0.1252	0.2310
10	0.0589	0.0743	0.0738	0.0817	0.2017

* Note: Values in brackets are the measured periods.

Table 2. Periods of Modes in sec for the Different Models

For the dynamic modal analysis of the lighthouse a design earthquake spectrum was used. It was inserted as a base excitation and the participation factors were calculated. These factors indicate the significance with which each mode participates in the vibrational energy of the whole structure. So modes with high participation factors must be included in the dynamic modal analysis. The results show that for masonry structures, as for most stiff, massive structures we have densely placed modes. So more than one mode participates. For the five models these factors are given in Tables 3 and 4. The participation factor depends on the direction of the seismic excitation as well as the particular characteristics of the geometry. For the examined models these characteristics include the existing slope of the upper part of the lighthouse (part A, B) and of course the quality of the material from which the parts of the structure have been constructed.

Model Modes	I	II	III	IV	V
1	46	16.40	16.56	30.29	13.31
2	0.77	2.72	2.46	8.96	27.14
3	0.29	2.53	2.57	23.27	0.04
4	24.84	6.58	6.57	11.74	29.48
5	5.48	5.56	5.63	0.02	6.80
6	6.46	0.89	1.41	0.002	0.12
7	12.53	29.30	29.27	13.47	16.91
8	0.84	35.70	35.14	2.88	2.03
9	2.23	0.11	0.20	9.32	0.21
10	0.55	0.19	0.20	0.04	3.97

Table 3. Participation Factors in Direction X (%) for the Different Models

Modes \ Model	I	II	III	IV	V
1	1.21	2.54	2.27	10.58	26.19
2	45.13	16.37	16.42	34.56	12.45
3	3.04	8.09	7.96	22.63	0.01
4	24.78	5.05	5.13	0.75	6.26
5	7.46	2.08	2.12	12.5	34.50
6	1.38	4.8	5.39	0.03	0.02
7	15.19	22.17	21.28	17.21	1.17
8	1.33	32.66	32.89	1.66	19.33
9	0.44	0.92	0.93	0.007	0.01
10	0.03	5.31	5.60	0.08	0.05

Table 4. Participation Factors in Direction Y (%) for the Different Models

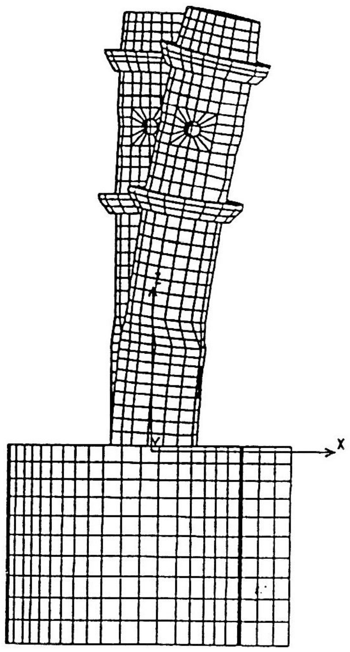

Figure 6.1 First Mode of Model III (0.932 Hz)

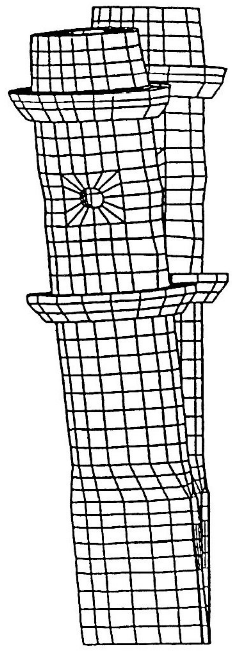

Figure 6.2 Fourth Mode of Model I (5.79 Hz)

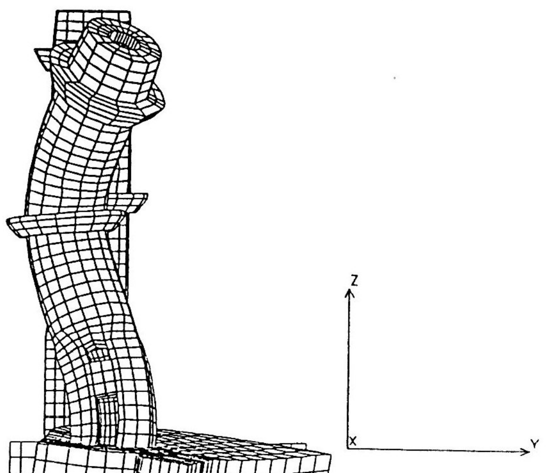

Figure 6.3 Seventh Mode of Model II (8.93 Hz)

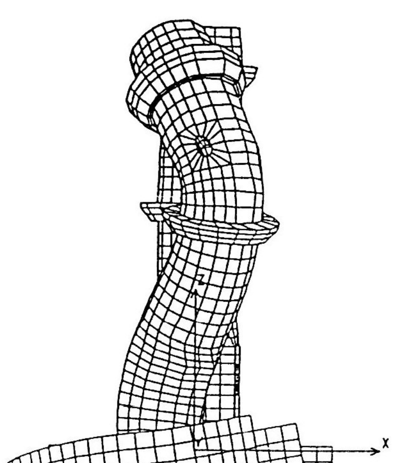

Figure 6.4 Eighth Mode of Model II (9.89 Hz)

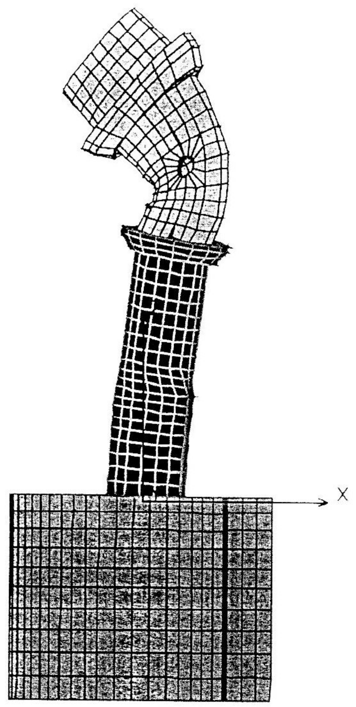

Figure 6.5 Fourth Mode of Model V (1.61 Hz)

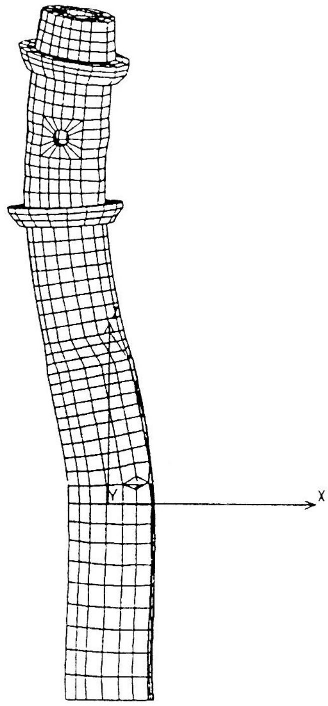

Figure 6.6 Seventh Mode of Model IV (7.11 Hz)

6 Discussion of Results

The effect of material modelling assumptions on the modal characteristics of monuments has been discussed with an application to a masonry lighthouse. The comparison of experimental data with structural analysis results and the calibration of the computational model such as to represent, with confidence the structural behaviour of a monumental structure is a complicated problem and can in general be solved on a case-by-case basis. For example, the first period of 0.44 sec, was not extracted from the results obtained in the beginning of this study (cf. Leftheris et al., 1995). Developing the parametric analysis which was used in this work, it was found that the base of the lighthouse was build from a different material than the rest of the structure. This agrees with the history of its construction (several reconstructions or repairs of some parts of the structure have been done after earthquakes or architectural changes). Although more complicated models which are based on non-linear material response have been proposed (cf. Swan and Cakmak, 1994) the value of the elastic material assumption, as it is done here, has not been reduced due to its simplicity and the reduced cost of the experimental investigation which is required.

In conslusion we should mention that the quality of the model, which can be used for structural strength and aseismic design and restoration purposes, is based on both material and structural assumptions. Neither of these two elements can be neglected in a restoration and a conservation project: Thus, experimental investigations on both the material level and on the structural level must be considered for a complete study.

Acknowledgements

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