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Seismic behaviour of old masonry structures

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ABSTRACT: Increasing interest is universally manifested towards structural reinstating of historic edifices Within this framework, series of studies were applied to Ottoman temples of the 16. Century; all with large masonry domes and located in heavy seismic zones around Istanbul. The findings which are going to constitute the starting point of a longterm international research program are summarized and discussed hereby.

1 INTRODUCTION

Increasing engineering and intellectual interest is manifested towards structural reinstating of historic monuments and edifices. Concept of reinstating could include complete restructuring in very heavily damaged and fully collapsed edifices. In such cases, installation of a hidden skeleton formed by contemporary materials ensuring adequate seismic resistance could be somehow foreseen while apparent components of the historic complex should be constructed by materials similar to original ones.

The engineering approach becomes less straightforward in case of partially damaged historic buildings or virtually not damaged edifices whose strength to seismic effect is, indeed, very doubtful. In these frequently observed cases, a structural intervention consisting of special repairing and bracing operations of very refined character would be needed. Discussions at the level of the use of modern materials in these operations are going on from the engineering ethic point of view as well as from art history and philosophy perspectives.

At any case, structural assessment studies become critically important. Their results have practical value at the level of science and art history as well as from preservation-restoration engineering point of view.

Within this framework, some major Ottoman temples, designed and erected by Sinan, the great Turkish masterbuilder of the 16. Century were investigated by the authors and some publications came out already in this topic as in the works of Karaesmen and Ünay (1988 and 1991) The present text was prepared to summarize and comment on available findings including results of some work very recently accomplished, from earthquake engineering point of view.

2 OVERVIEW OF MASONRY DOMES

2.1 General

Domed structures are recognized to be of solemn character and to reflect an unusual spatial effect. In the temples, regardless of the religion or the sect, this effect bears a particular, spritual and almost enigmatic intensity. Indeed the main dome constitutes both the ritual center and the basis of engineering-architectural prestige, especially when it is conceived and constructed as a shell of revolution. Generally speaking, difficulty of controlling the effect of the thrust action under gravity loads and the search to ensure good structural compatibility between the dome itself and its supporting structural components under seismic loads were main obstacles to construct very wide-spanning masonry domes of revolution-shell form. Special components, externally bracing the large spanning main domes were needed; the number and size of them increasing through the ages as in the case of Haghia Sophia, at the price of sacrificing the original visual exterior elegance and/or balance of the edifice.

An ingenious solution was arrived by contributions of Sinan, great Ottoman masterbuilder of the 16. Century. Partial surrounding cupolas supported the main dome at level of its circumferential belt -called also drum- which is a basic component of the skeleton and relies piers and other bottom structural elements, to the dome. Skeleton elements were given geometrical forms and sizes such that a perfect load transmission mechanism for both gravity loads and seismic action was ensured. The skecthes in Figure 1 outlines the structural approach settled by Sinan for large domed temples which constitued classical basis for similar edifices constructed later in all Muslim countries. (See Kuban (1987) and Kuran (1987)).

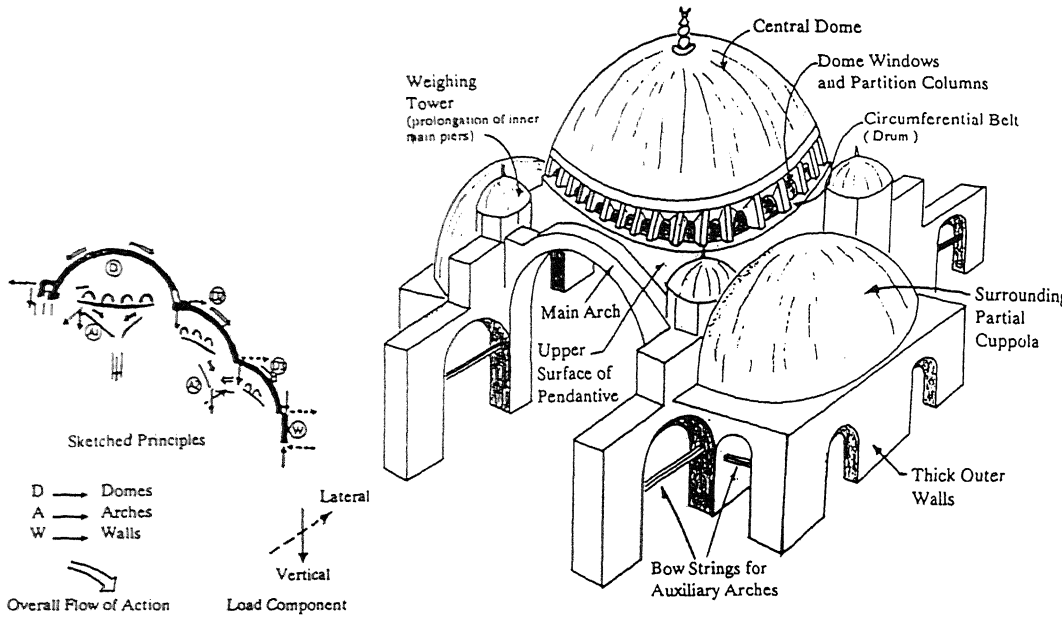

Figure 1. Representation of typical components and action flow mechanism in Ottoman domed buildings

2.2 Constructional and structural features:

Upper level elements (main dome, its drum, partial surrounding coupolas) and some of lower level components (arches, secondary partial cupolas etc.), are all formed by curved surfaces and lines. Neighbouring vertical elements (interior piers or columns and outer walls) are connected to these curved components either directly or through pendantives, three dimensional corner elements of high geometrical complexity. The whole skeleton forms a complicated space structure which necessitates rather sophisticated investigation as for its assessment for reinstating purposes. Vertical components, drums and small secondary arches are generally constructed in mortared stone masonry while shallow bricks are used in construction of all other curved components. The structural complexity already originated from spatial forms is, then, amplified by the diversity of the material used in load bearing components. (Karaesmen (1991), Rumpier (1956)).

Structural behaviour under gravity loads is mostly governed by a mechanism of controlling thrust action around the main dome which generally lies in compression state both for meridional and hoop stresses. Surrounding partial cupolas when adequately formed and sized, contributes to this control supporting the main dome laterally and transmitting all loads to thick external walls whereas main arches, subjected to combined effect of flexure and torsion, transfer a good portion of upper level loads directly to interior piers.

Load transmission mechanism under seismic action has more complicated features which could be outlined as follows: i) The main dome is settled on its circumferential drum through a certain number of slender columns which form partitions between elegant windows located at the lower flank of the dome. The dinamic effect of the upper system is especially carried by the above mentioned columns that are being subject to unexpected shear forces during earthquakes. ii) Compatibility between the drum and main interior piers is ensured by pendantives. Their and spatial contructional complexity geometrical features are such that they could be affected during earthquakes by tensile stresses approaching the mortar strength in some sections. Although high binding quality is recognized in Sinan's specially manufactured mortars, pendantives are looking like critical components with regard to seismic effect. iii) As far as vertical structural components are concerned, thick external walls are seismicly solicited rather uniformly over their surrounding length since partial cupolas, smaller secondary arches and cupolas are connected to them at various levels of their surfaces. Consequently lateral loading does not create an intense zonal effect and there is apparently no place to expect critical stress conditions in those walls. As for interior piers, they are obviously more critically solicited at their base during earthquakes and their lateral displacement tendencies would not be at a negligeable degree.

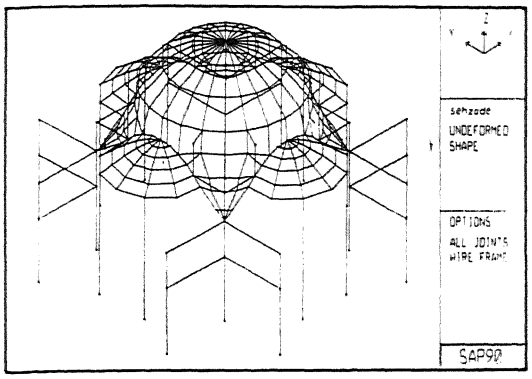

Figure 2. Structural model of Sehzade Mosque

3 CASE STUDIES

3.1 Overal approach

Two of major mosques designed and constructed by Sinan in Istanbul were investigated. One, called Sehzade (Prince) Mosque is considered as the most progressive achievement of his early period and other, Mihrimah Sultan Mosque as a pure masterpiece and a wonderful example of his masterly period products, where "architecture-structure" alliance is perfect.

Various type of finite element techniques were used in these investigations. Sehzade Mosque is reported as being perfectly earthquake resistant since none of the historic seismic disasters happened in Istanbul and its vicinity hazarded it during its life span of 450 years. Finite element applications for elastic linear behaviour looked like sufficient at a preliminary stage to evaluate load transmission mechanism. As for the other edifice, it has been reported (unfortunately not writtenly) that it was somehow touched by the 1894 earthquake, one of the most violents ever witnessed in metropolitan urban areas in the world. Lateral differential displacements on the columns had been observed as well as cracks on the main dome and on the borders of main arches neighbouring pendantives. However the hazard was relatively unimportant with regard to the intensity of this devastating disaster (later estimated around X at MKS system) and the temple was easily and quickly repaired, a certain seismic vulnerability has been observed, in this occasion. Therefore, more detailed analysis approaches have been adopted for this temple.

3.2 Sehzade (Prince) Mosque investigations

Overall building shape and features of structural components of this edifice are fitting to general classical system of Ottoman domed edifices described in Figure 1. The central dome has a partial spherical form with a varying thickness approximated to 50 cm. in average. The diameter of the sectional circle resting on the drum is 19,50 m. Four partial cupolas surroundthe drum and each of them is supported at lower levels by two smaller partial cupolas as described in the load transmission pattern sketch in Figure 1.

The temple was analytically investigated in several ways. The main dome alone was analyzed first, being considered as formed by partial spherical slices clamped on the drum. Since the fulfilment of compatibilty conditions between the dome and other neighbouring elements is leading to unrealistic structural considerations, other models were needed.

The model reflecting the whole structure as presented in Figure 2 was adopted with an idealization approach of assembling 240 shell elements and 200 frame elements. The detailed description of the upper structure is given in Figure 3. The total load of the system including the snow was evaluated as 160.000 kN. Seismic action was approximated to 16.000 kN of lateral load and its investigation was based on the spectral analysis with consideration of spectrum features of the soil on which the edifice was settled. Numerical results revealed interesting features for overall comprehension of the load transmission mechanism. As for the earthquake aspect, the following points confirming also general considerations described in Chapter 2 above were strikingly observed: i) Maximum shear stress under seismic action was evaluated 0,3 N/mm in the short partition columns of windows on the lower flank of the main dome. For local limestones, this stress reveals rather close to allowable limit evaluated as 0,42 N/mm. This finding shows the already underlined critical importance of the short partition columns at the lower flank of the main dome. ii) Skeleton elements of the central space (main dome, drum, four main arches and four pendantives) were connected to thick outer walls by surrounding bracing partial cupolas and also a series of smaller inner cupolas and arches at lower

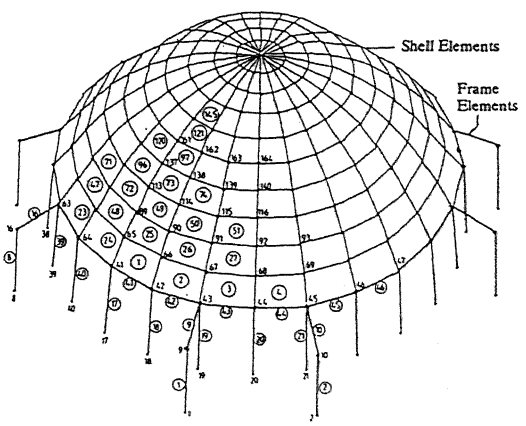

Figure 3. Sehzade Mosque, upper structure

levels. Bow string arches which were constructed in these areas (Figure 1) contributed to transmission of the lateral seismic action from the main central pier to the thick outer wall. 28 % of the total lateral load was carried by these elements, showing cleverness of the design and contruction of the overall skeleton where all components had a structural significance as well as functional and esthetical meaning.

3.3 Studies on Mihrimah Sultan Mosque

Mihrimah Sultan Mosque that is erected to the name of the daughter of Emperor Suleiman the Magnificent is a product of the masterly period of the Great Sinan (Figure 4). This edifice is recognized to have an interior space of a unique refinement. The spatial beauty of the temple is attributed to its daring structural system. There are no externally bracing partial cupolas in this extraordinary structure whose transmission of both seismic and gravity loads is ensured essentially by thin elegant arches and nice looking pendantives. The dome is known as having the largest sizes ever reached for an unbraced shell of revolution with its diameter of 21 m. and its 38 m. of height from the ground level.

Various types of investigations were also applied to this temple. Since a partial hazard had been reportedly witnessed during the 1894 seismic disaster, some sophisticated details were foreseen in the analysis of this edifice.

First of all, it was considered essential to check whether a basic seismic weakness would govern the behaviour of the dome or not. Within this purpose, a model for finite element analysis of the dome alone considered as clamped on its drum was chosen. The numerical findings have shown that under combined effect of the seismic action and gravity loads, no critical tensile stresses were created in the dome sections. On the other hand the compressive stresses were revealed much lower than the strength to be expected for a mortared brick continuum. If some cracks had been observed on dome surfaces, during the 1894 quake, this should be rather due to larger deformations occurring in the components of the lower structural system. However the oral reports on the disastrous effect could be considered only partly reliable, it is generally accepted that the four main piers and four pendantives of the skeleton had been subjected to differential lateral displacements causing authomatically lateral support settlements for the drum and main dome.

At further stage, a comparative analysis logic was adopted. Within this framework, two models both corresponding to the whole skeleton of the edifice were developed.

First model was aiming to reduce the structure to the components without considering none of the architectural elements at the bottom of the four main arches, namely, the secondary arches and small cupolas covering auxilary praying zones and also

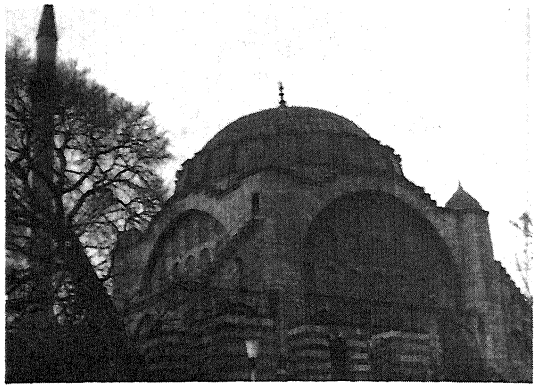

Figure 4. General view of Mihrimah Sultan Mosque

arched exterior walls of the building. Main arches and pendantives of the systems are descending to unusually low levels, in a way magnifying the visual effect of these already elegant components. The above mentioned elements of the very low levels were not looking like strongly contributive at a first glance. Therefore, a model neglecting them would be considered sufficently reliable. (Figure 5)

But, numerical findings have revealed that, effect of the seismic action investigated with a sensitive spectral analysis was reaching to very critical levels that apt to cause easily the full collapse of the columns and consequently of the building. On the other hand, the period for the prevailing (first) vibration mode was evaluated to be 2,1 seconds which was looking little bit too high even for this light looking structure formed by rather slender components. These immediate results were suggesting that the contribution of the bottom level elements could and should not be underestimated. This observation was also fitting to above mentioned finding of the Sehzade Mehmet Mosque analysis related to structurally bracing significance of even very small inner components.

A more elaborated second model was, then, needed to reflect the structural behaviour of the system more realistically. As seen on Figure 6, all bottom inner components and even one series of external cupolas next to the building with their columns, and bow string arches were inserted into the model. The period for the first vibration mode was reduced to 1.6 seconds that was looking like a more reliable value.

In both analysis, the total weight of the building was taken 90.000 kN. As for the seismic action, soil spectrum considerations and slenderness of the skeleton yielded in a seismic coefficient around 11 % for the first mode. The critical column shears and moments for the case maximizing the action effect in x direction are summarized in Figure 7.

Moments and shears are not very small in either direction as indicated on the figure, since there is a stiffness unsymmetry in the skeleton.

For comparison purposes some values, obtained from the analysis neglecting bottom components, are indicated under bracket on this figure. Both moments and shear forces differ a lot from one model to the other as expected. It should be, in addition, underlined that lack of detailed information on the shape and depth of the foundations shadowed somewhat geometrical sensitivity of both models.

On the other hand, the analysis of this elaborated model indicated the zones where flexural effects and stresses would be maximized by seismic action when added to gravity loads. Associated directions of the complete quadratic combination (CQC) results of spectral analysis are determined by imposing the displacements of the first mode of vibration to the critical element solicited. As for the evaluation of the most critical combined effect, the associated signs of the seismic action were taken into consideration.

As for the aspect of crack formation risk of the problem, the numerical computer results were checked by the aid of coloured graphic outputs. Zones of maximum tensile stresses were observed to locate in pendantives near to the middle of the main arches. Direction of the principal tensile stress was computed to be in a direction such that formation of a crack parallel to the curved axis of the arch could be expected. Computational aspect of the cracking problem is summarized in Figure 8 where flexural moments are sketched as computer output in terms of t-m/m.

4 CONCLUDING REMARKS

Investigations and assessment studies forwarded into two masterly examples of the large domed historic masonry buildings aimed to develop general knowledge extendable to all other major old edifices built in masonry. More specific findings were also obtained concerning the mentioned two monuments in order to orient an international research program

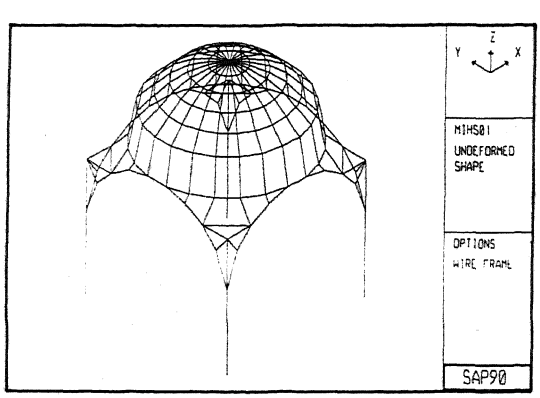

Figure 5. Model for Mihrimah Sultan Mosque without lower structure

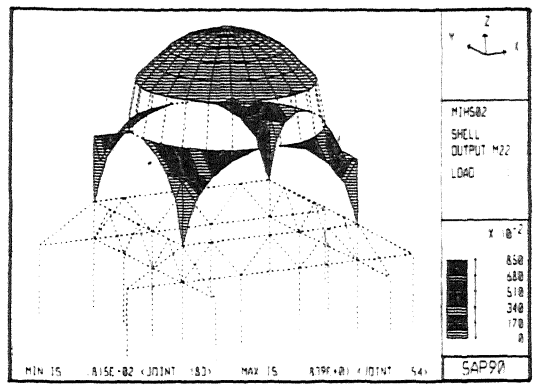

Figure 6. Structural model of Mihrimah Sultan Mosque with lower structure

on historic Ottoman edifices, in seismic zones. The following points could be remarked, as conclusion.

a. Historic edifices of major importance in seismic zones should be structurally evaluated in a systematic way without waiting happening of disastrous hazards. In these systematic assessment studies, importance given to soil aspect as well as to detailed information of underground components, should be increased.

b. Idealized model analysis based on detailed computer culculations is a good approach, in general. But rough approximations underestimating the contribution of some of minor components to seismic response could lead to major errors. Modelling accuracy turns out to be of primary importance in studies of seismic behaviour. Possibility of checking and perfecting preliminary models by system identification techniques should also be planned for unusually complex cases, as it is foreseen in further stages of investigations on Mihrimah Sultan Mosque.

c. Studies on crack occurrence and its effect on the redistribution phenomenon should be given particular emphasis in the future. In this purpose, space elements thick as one fifth of the total thickness of the arches and pendantives were considered in the zones with high risks of cracks, in investigations presented here. Determination of spatical geometry of such elements should also take into account sensitively exact locations and sizes of bricks and mortar, as is aspired in the next step of the authors' studies.

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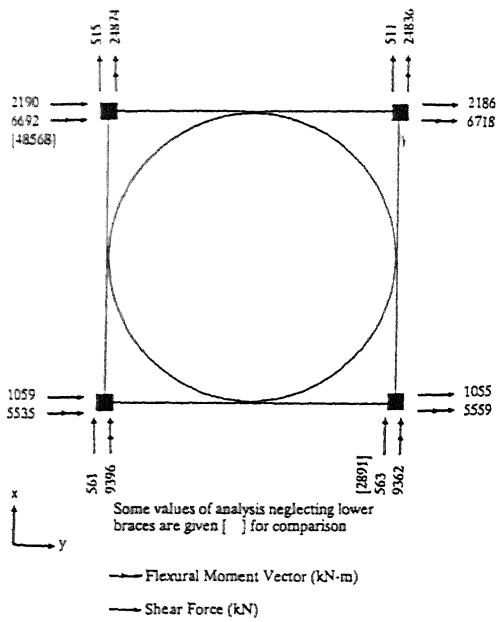

Figure 7. Shear and moment values at bases of four main piers (sketched plan view)

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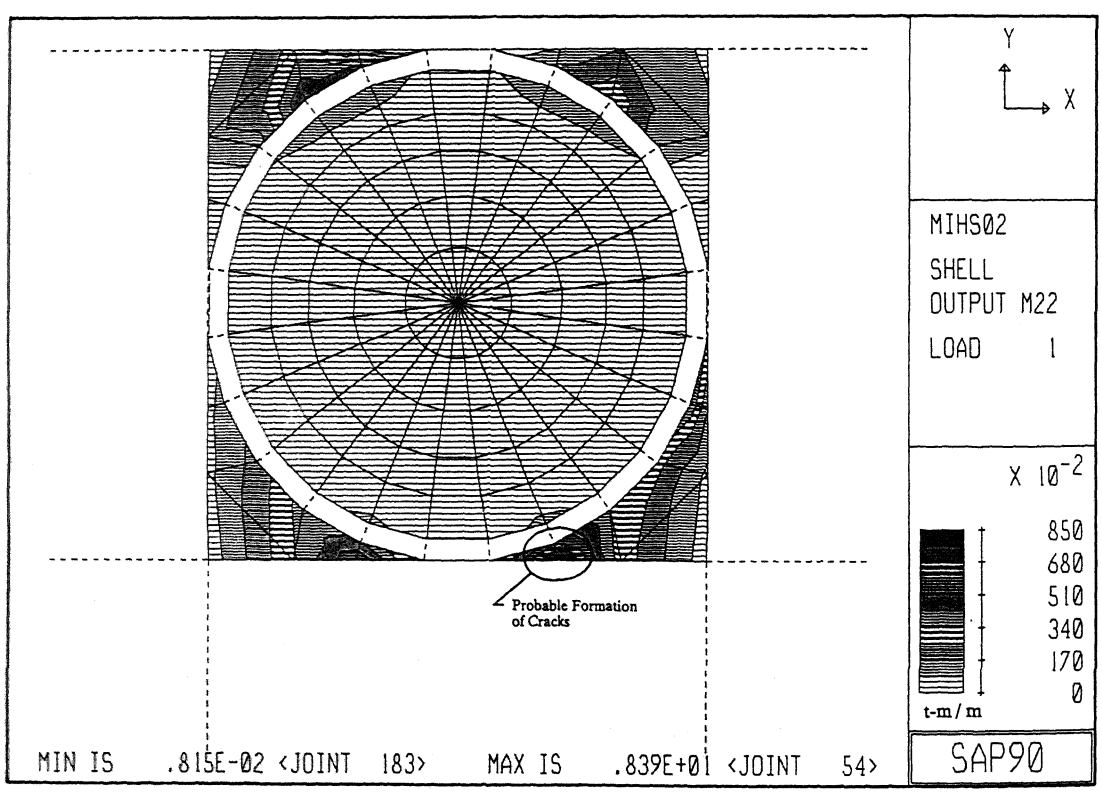

Figure 8. Flexural moment intensity map of shells of Mihrimah Sultan Mosque