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EFFECT OF DAMAGE ON THE DYNAMIC CHARACTERISTICS OF ST. NICHOLAS CATHEDRAL IN CYPRUS

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Abstract. *The protection of monuments from aging and natural hazards, such as earthquakes, is very important since such structures are part of the cultural heritage of many countries around the world. In order to protect them from earthquakes, their structural system has to be identified and their capacity to withstand dynamic loads has to be clearly understood. Due to the large size of such structures and the limitations imposed by antiquities departments on the methods that can be used to obtain the properties of the materials of these structures and their dynamic characteristics, the ambient vibration survey method seems to be the most appropriate one to be used.*

Once the dynamic characteristics are identified, they will form a bench mark and any deviation in these parameters will be used for the identification and localization of damage caused to the structure, either due to environmental factors and aging, or due to an earthquake. In this work the dynamic characteristics of St. Nicholas Cathedral obtained through ambient vibration survey and the subsequent calibrated FE model are presented. Then a numerical sensitivity analysis is performed, in which damage in inflicted at vulnerable sections of the structure and the effects of this damage on the dynamic characteristics of the structure are recorded. Finally, conclusions are drawn on the type of sensors and locations they should be placed, as well as on the effectiveness of a monitoring system in identifying and localizing damage on the structure.

1 INTRODUCTION

In Cyprus there are plenty of historic monuments, all emerging from the various conquerors of the island who left an indelible mark on the structural heritage. These structures are invaluable, both in cultural and architectural terms. Nowadays there is an ever increasing sensitivity to preserve these monuments through rehabilitation and maintenance. For these historic structures, most of which are constructed of masonry, the assessment of their structural performance is based mostly on modal testing.

However, there are concerns in the application of modal testing (which is based on linear elastic behaviour of structures) to historic masonry monuments due to the complexities of these systems; such complexities include for example the assembly of mortar and masonry units via mortar joints. Field tests and checks on similar structures showed that the linearity assumption is a valid approximation and the analyses prompted accurate results [1].

Due to the sensitive nature of historic monuments, the use of excitators such as impact hammers or shakers is often restricted or prohibited and the tests are normally performed by using the Ambient Vibration Survey (AVS) technique. The results are often used to calibrate a Finite Element (FE) model that can be used for further analyses and for damage identification procedures [2].

Another issue of concern for masonry structures is their vulnerability to earthquakes. The historical investigation on the understudy monument carried-out in section 2 of this study, provides information that the St Nicholas Cathedral has been damaged by earthquakes. Monitoring and field tests can help assess their condition after earthquakes and investigate the effectiveness of any protecting countermeasures [3].

The current study carries-out a numerical damage assessment on the St Nicholas Cathedral in Famagusta, Cyprus. The dynamic characteristics of the monument as obtained from AVS testing, contributed in the calibration of the developed FE models and in the planning of the monitoring strategy that is already implemented at St Nicholas Cathedral. The initial FE models were calibrated basically through modification of the Young's modulus in order to minimise the differences in the frequencies and the mode shapes between the FE models and the measurements. The calibrated models were used to estimate changes in the frequencies after damage has been induced at several locations on the structure, which were identified through a numerical seismic analysis performed on the monument [4].

2 DESCRIPTION OF ST NICHOLAS CATHEDRAL

The earliest documents that mention the cathedral of St. Nicholas at Famagusta go back to 1300 AD. Although the chronicles of Amadi and Florio Bustron state that the construction began in 1308, it is certain that the work was under way from the 3rd August 1300, as reported in the Genoese records of Famagusta published by Cavaliere Desimoni [5]. It was the Bishop of Famagusta at that time (Bishop Guy) who initiated and financed the construction of the St. Nicholas Cathedral. After Bishop Guy's death, his successor Baldwin Lambert continued and completed the construction of the Cathedral. St. Nicholas Cathedral was the appointed place for the coronation of the Lusignan kings as Kings of Jerusalem, after they had been crowned as Kings of Cyprus at the capital of the island, Nicosia. This is probably why the Gothic style of the structure closely resembles that of Rheims Cathedral in Paris, France. The cathedral was damaged by earthquakes in 1546, 1568, and 1735. After the Ottoman conquest of 1571, the cathedral was converted into a mosque with the addition of a mihrab and a minaret and complete removal of internal decorations. Since then it is being used as a mosque. The style of the structure indicates that the architects and the sculptors of the cathedral were brought in from the Champagne region, France. The St. Nicholas cathedral consists of a nave of seven bays ending in a polygonal apse flanked by aisles ending in apsidal chapels of similar shape (Figure 1). It is a 50m long, 24m wide limestone structure with a height of about 29m. The thickness of the walls is in general 1m while that of the vaults is 0.75m [5].

Figure 1: St Nicholas Cathedral

3 FINITE ELEMENT MODELLING

The field testing was carried out in association with the Kibris Turk Mimar ve Muhendis Odaları Birligi (KTMMOB) under the EuropeAid funded project “Earthquake vulnerability of historical monuments in Cyprus”. The FE modelling in this work was implemented by the KTMMOB partner and the purpose of this section is to provide the main steps of that FE modelling process. The details of the latter can be found in [4] and [6].

For the St Nicholas Cathedral three different in details and complexity, 3D FE models have been developed with the level of complexity progressively increasing with each model [6]. The first and second models use only 2D shell elements for all structural members, but in the second model the minarets and the tower staircase were included. For the third model, the 2D shell elements were replaced with 3D solid elements for the peripheral abutments, internal columns and the western façade peripheral wall, to provide a more accurate representation of members with thick cross sections. All other details (material properties, boundary conditions) were the same for the three models.

Their allocated thickness was based on detailed on-site measurements. Prior to the FE modelling, several non-destructive testing (NDT) have been carried out using equipment such as the rock hammer, the ultrasonic pulse velocity, the ground penetrating radar etc, in order to estimate the mechanical properties of the building material and assess the construction details (i.e. foundation type) and the structural condition of the monuments (surface-cracks depth etc). With this information, the material properties such as compressive strength and the Young’s modulus of elasticity were set for the FE models. To take into consideration the weathering of the stone, three different masonries were assigned to different sections depending on their exposure.

The numerical results presented in this study are obtained from the linear elastic modal analysis (using the updated FE model after the Young’s modulus was adjusted to match the experimental values) after the work in [4] and [6].

4 VIBRATION TESTING

4.1 Testing procedure

A variety of techniques exist for field modal testing, depending on the availability of equipment, the type of structure and the operational conditions. When the input force is not measured, the analysis is undertaken using response data, and is better known as output-only analysis [8]. The modal parameters are subsequently extracted from the measured responses using a wide variety of methods which are nowadays implemented in powerful software such as ARTeMIS [9].

The output-only analysis is associated almost exclusively with the ambient vibration survey (AVS) method [10], although in some cases human activities can be used to excite the structure especially for tests on footbridges and floors. Ambient vibrations are the vibrations caused by excitation experienced by a structure under its normal operating conditions, therefore allowing the structure to remain open. Based on equipment's availability described in [11] and information from previous tests on similar structures, described in [1], it was decided to adopt the AVS approach.

The field testing on the St Nicholas cathedral is described in detail in [11].

5 DATA ANALYSIS

The acquired data obtained from the measurements were analyzed using DASYLab 9.0 [12] and ARTeMIS Extractor Pro 5.2 [9]. The first software was primarily used to obtain the frequencies of vibration contained in the signals using Fast Fourier Transform. The second software which is used exclusively for output-only analysis was utilised to confirm the frequencies obtained from DASYLab but at the same time revealing the mode shapes of the structure that correspond to the identified frequencies. The analysis in ARTeMIS is implemented using the Frequency Domain Decomposition (FDD) and the Stochastic Subspace Identification (SSI) methods [13]. A Hanning window with 67% overlapping and a frequency resolution of 0.015Hz were used. For the correlation of mode shapes, the Modal Assurance Criterion (MAC) has been used [14].

5.1 Dynamic characteristics of the St Nicholas Cathedral

The details of the modal parameter identification of St Nicholas cathedral can be found in [11]. In this study only the results are presented in a tabulated form: the frequencies and mass participation factors from the numerical analysis performed in SAP2000 are listed in Table 1.

In addition, in Table 1 only measured frequencies associated with identified mode shapes are listed and the correlation of the identified mode shapes with their numerical counterpart is expressed using the MAC values. The mode shape correlation has been performed by the FEMtools software which is using the measured data to perform FE model correlation and calibration [15].

Mode	Calculated Freq. Hz	Measured Freq. Hz	MAC	Mode Type	UX	UY
1	0.98	0.98	0.82	Longitudinal	0.6400	0.0126
2	0.99	1.04	0.85	Lateral	0.0107	0.6500
3	1.33	---		Torsional	0.0002	0.0182
4	1.54	1.40	0.89	Lateral	0.0012	0.0005
5	1.64	---		Torsional	0.0000	0.0559
6	1.82	---		Torsional	0.0001	0.0170

Mode	Calculated Freq. Hz	Measured Freq. Hz	MAC	Mode Type	UX	UY
7	1.94	---		Torsional	0.0263	0.0003
8	2.17	---		Torsional	0.0119	0.0000
9	2.30	---		Torsional	0.0051	0.0037
10	2.40	---		Torsional	0.0149	0.0000
11	2.48	---		Torsional	0.0491	0.0085
12	2.55	---		Torsional	0.0554	0.0033

Table 1: Measured and numerical modal parameters for St. Nicholas Cathedral

The mode shapes of the first three translational modes from the updated FE model are shown in Figure 2.

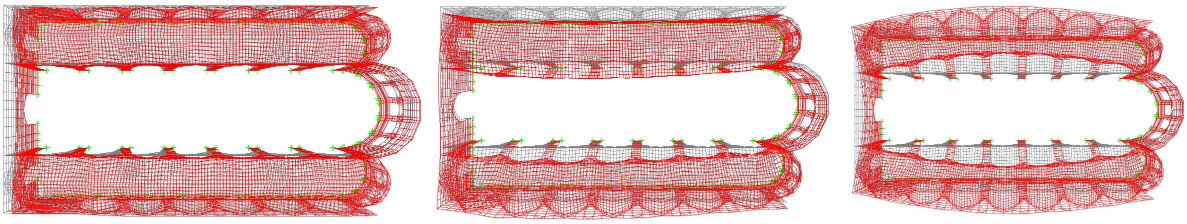

Figure 2: a) 1st longitudinal mode at 0.98Hz b)1st lateral mode, and c) 2nd lateral mode

6 FE MODEL UPDATING

Normally prior to FE model updating (manual or automated), sensitivity analysis is carried out to indicate the important parameters. In this study, a first attempt was made using only modulus of elasticity, E, in order to give an insight for the modes captured but not identified via their mode shapes due to lack of measured points. Other uncertain parameters that are often used in the updating procedure for masonry structures can include the connectivity between structural members (mortar joint), stone's density, etc [16].

The main parameter affecting the dynamic characteristics of masonry monuments is the E value of the stone. This value varies not only between different monuments but even comparing members of the same structure. In this study it was initially assumed that all structural members of the structure have the same value, i.e. a homogeneous distribution in all members. Although other researchers [17] divide the structure using different E for each divided section, the updating process with this assumption provided good correlation between the numerical and measured data, thus a single value for E was considered.

In the current study a simple model (shell elements and considering only one type of masonry) has been employed in the updating procedure. For this FE model the modulus of elasticity of the stone of which the monument is made of was initially set to 603 MPa, based on some compressive tests that were performed on the stone. With that modulus of elasticity the fundamental frequency was 0.834 Hz. In order to match the first recorded frequency shown in Table 1, the modulus of elasticity of all the elements was changed to 702 MPa.

7 RESPONSE SPECTRUM ANALYSIS

The seismic performance of the St Nicholas Cathedral was investigated numerically by Cagnan [4]. She used the three models described in section 3, to study the behaviour of the monument under earthquake loading of 475 years return period and for 5% damping. The results of the earthquake response spectrum analysis indicated different structural behaviour among the models, where the induced tensile stresses exceeded the calculated structural capacities. The models developed only with shell elements indicated the critical members to be the internal columns, and depending on the condition of the weathered masonry, the crown points of the vaults, the flying buttresses, and the peripheral abutments (Figure 3a-d). The model with the incorporated solid elements restricted definite damage only to the flying buttresses and under conditions to the crown points of the vaults (similar locations as depicted in Figure 3a). The obtained results from Cagnan [4] are shown below.

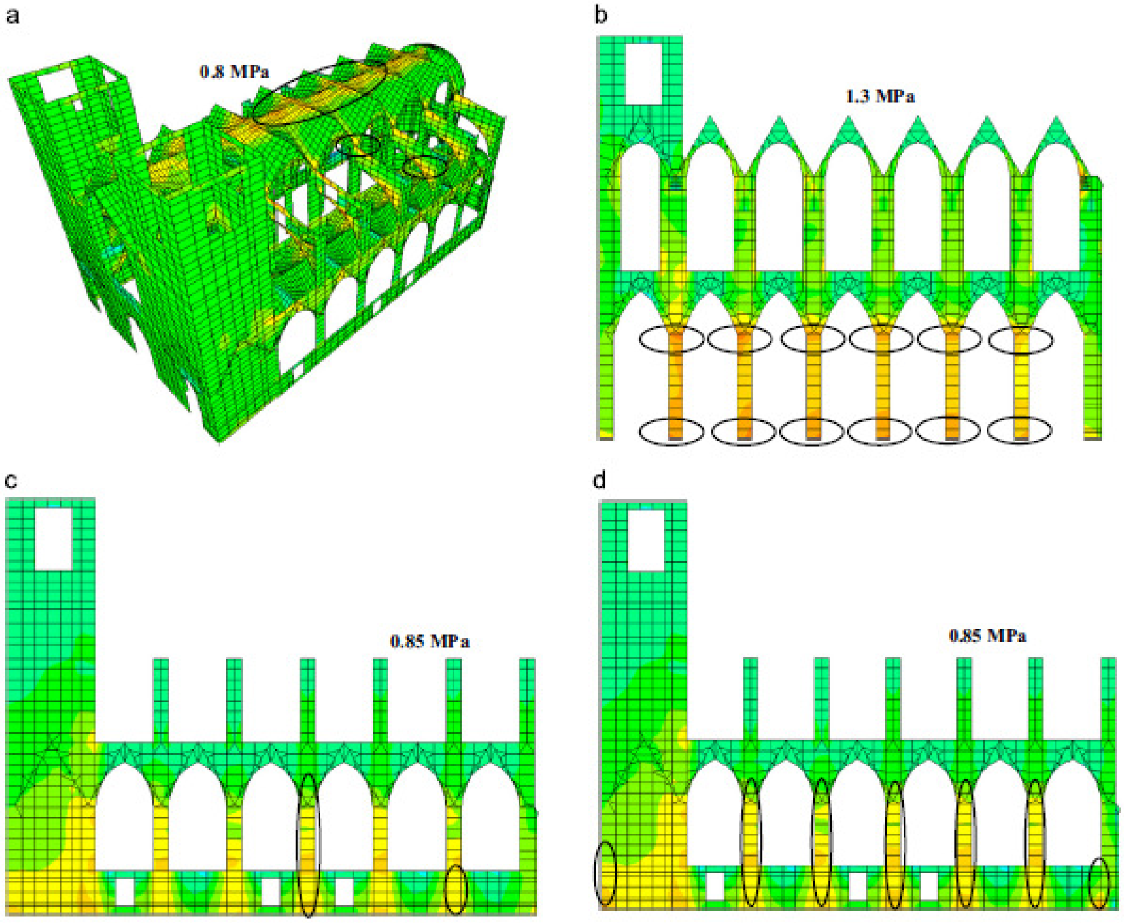

Figure 3: Stress distributions (a) flying buttresses and vaults (b) internal column capitals and bases ;(c) peripheral abutment(d) peripheral abutments (after Cagnan[4]).

Considering the performance of the three models, Cagnan concluded that as the results of model 3 are consistent with damage sustained by the structure reported in historical documents, this model can be considered to represent better the actual structural behaviour of the monument. She concluded that the more simple shell element models are adequate to provide an insight of the dynamic characteristics of complex structures but they may have limitations when coming to stress distribution analyses.

8 SIMULATED DAMAGE SCENARIOS

Considering the findings of the previous section after the work in [4], a damage assessment has been carried-out examining various damage scenarios. The objective was to check if induced damage on the structure at different locations can be identified solely by changes in the frequencies. Generally, in literature a limit of 5% change in frequencies is considered as significant; smaller changes can be attributed to ambient conditions variations such as temperature, wind etc [18, 19]. This limit has been adopted in this study to indicate the presence of damage in the monument.

Having in mind that a monitoring system is installed on the monument this sensitivity analysis will provide a useful insight of its capabilities.

For every damage scenario, three damage cases are considered, with progressive reduction of masonry's Young modulus, E , from the initial value of 702MPa:

1. 25% damage=25% reduction = 527MPa
2. 50% reduction = 351 MPa
3. 75% reduction = 176MPa.

The chosen damage locations are as shown in Figure 3. Although the results of the more detailed FE model are considered as more accurate, also the findings of the simpler FE models have been considered in the investigation. The damage scenarios and their adverse effect against the 5% frequencies change limit are discussed below.

8.1 Damage scenario 1

This scenario is focused on the behaviour of the flying buttresses. Two damaged locations have been considered as in figure 3a (circled yellow areas): 1) flying buttress-vault connection and 2) underside of flying buttress. Initially only a single flying buttress has been examined under the three damaged cases (progressive, 25%; 50%; 75%, E reduction). The results showed almost no changes in frequencies; the highest change calculated was 0.3%.

8.2 Damage scenario 2

Following the examination of a single flying buttress, the next step was to assume that all the members on one side have been damaged in the same way as in scenario 1. The effect of this damage scenario on frequencies was insignificant with the highest value calculated at 0.9%.

8.3 Damage scenario 3

For this scenario it was considered that all twelve flying-buttresses on both sides are damaged. The changes on frequencies were well below the 5% limit; a variation of 1.8% was calculated for the fourth mode (second lateral).

8.4 Damage scenario 4

In addition to the damage on the flying-buttresses it is considered that all the internal columns have sustained some form of damage. As the damage source has enough intensity to affect all the internal columns, it is safe to assume that the weakest part of the monument (that is the flying-buttresses), are all damaged too. Therefore, the damage described in scenario 3 is extended herein on the twelve internal columns. The damage is simulated with reduction in E on the top and bottom 2 elements (Figure 3b). The results showed that only for the worst case (75% reduction of E) the changes in the frequencies of the two lateral modes exceeded the limit of 5% (6.5% and 5.6% respectively); all other modes had smaller changes. However, the most important observation is the modal re-ordering of the two first modes: the lateral mode is now representing the first mode of the structure whereas the longitudinal mode appears as the second mode.

8.5 Damage scenario 5

For the last scenario, it is assumed that the 5 external columns on one side only, as in Figure 3d, are damaged, in addition to the damaged structural members of scenario 4. The damage is induced on the 12 elements below each column's capital. The same amount of damage is induced simultaneously on external and internal columns; the reduction on the flying-buttresses elements is kept constant at 75%. The analysis showed that for 25% reduction in columns' Young's modulus the frequency changes are not considered as alarming. At 50%, both lateral modes exhibit reduction in their frequencies of over 6%. For 75% reduction this difference is increased to 10%. All other modes are approaching the 5% limit. The modal re-ordering of the first two modes is again observed in this scenario.

8.6 Summary of results

The damage assessment results described above are summarised in Table 2. For the assessment the first ten vibration modes have been considered. It is shown that for the first three scenarios no significant changes in frequencies were observed, even for 75% induced damage on the selected members. For scenarios 4 and 5, the damage is affecting more modes 1 and 4 (lateral modes) and modal re-ordering is also observed.

Mode No & Type	**DS1** 75% Damage	**DS2** 75% Damage	**DS3** 75% Damage	**DS4** 75% Damage	**DS5** 50% Damage	**DS5** 75% Damage
1- longid.	-0.02	0.08	0.22	6.56 lateral	6.21 lateral	10.84 lateral
2- lateral	-0.30	0.19	0.73	2.45 longid.	2.55 longid.	4.92 longid.
3- torsional	0.06	0.76	1.38	3.86	3.42	5.19
4- lateral	0.15	0.93	1.80	5.62	6.09	9.51
5- torsional	0.23	0.31	0.40	2.05	1.90	3.36
6- torsional	0.27	0.88	1.43	3.14	2.92	4.29
7- torsional	-0.06	0.18	0.42	1.95	1.67	2.76
8- torsional	-0.01	0.51	1.04	2.23	2.23	3.22
9- torsional	0.19	0.49	1.15	3.98	3.03	4.69
10-torsional	0.01	0.13	0.28	1.41	1.06	1.76

Table 2: Summarised results of % frequencies changes for damage scenarios (DS).

9 CONCLUSIONS

In this paper the results of a numerical damage assessment for the St Nicholas Cathedral in Famagusta, Cyprus, were presented. For the assessment, calibrated FE models from field testing were used. The objective was to check if induced damage at different locations can be identified by solely changes in the frequencies.

The critical locations which are vulnerable after an earthquake have been identified from the numerical seismic assessment carried out in [4]. The study indicated that the flying buttresses are the most critical structural parts of the monument, which lies in agreement with previous damage sustained by the monument during an earthquake. In addition, other locations such as the internal and external columns and abutments have been considered in the damage assessment.

The damage has been introduced in the selected members as reduction of the masonry's Young's modulus. Three steps of 25% progressive reduction have been applied.

The results showed that severe damage at some parts of the flying buttresses cannot be detected by frequency changes. Additional severe damage to the internal columns can cause concerns over the condition of the structure, even though the damage affects only the lateral modes. Basically, only the extension of 75% damage to the external columns can clearly indicate the presence of damage. This shows that depending solely on frequencies in a damage assessment it is not very effective. High levels of damage are required to cause alarming variations in frequencies. It is well known, that this approach is the first and simplest step in a damage assessment; subsequent studies will include in the assessment the mode shapes (obtained from the sensors of the installed monitoring scheme) and damage identification techniques to investigate whether better evidence for damage detection can be provided. It is clear that monitoring of the individual behaviour of selected structural members is required, when only the frequencies are considered.

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