Assessment of Dynamic Behaviours of St. Mamas Church and St. Nicholas Cathedral, Cyprus

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SUMMARY :

In this study, the seismic vulnerabilities of St. Mamas Church (Morphou, Cyprus) and St. Nicholas Cathedral (Famagusta, Cyprus) under a probable major earthquake were assessed. St. Nicholas Cathedral was constructed in the 14th century during which Cyprus was under Lusinian rule. This structure is one of the monumental symbols of the Gothic city center of Famagusta with its 24m-50m plan area and unique architecture. With the island entering Ottomman rule back in 1571, St. Nicholas Cathedral was converted into a mosque by the addition of a minarret to its Northwestern corner (Lala Mustafa Pasa Mosque). Today, it is still in service as a mosque. Historical traveller accounts indicate that St. Nicholas Cathedral sustained earthquake damage at least three times during its service life. St. Mamas Church, for which no historical accounts of previously sustained earthquake damage exist, was constructed in the 16th century with a plan area of 9m-18m. Regarding architectural style, this structure is considerably different from the St. Nicholas Cathedral. It has been pointed out as one of the unique examples of the Franco-Byzantaine hybrit architectural style on the island by several art historians. This structure is, currently, in use as a museum. Three dimesional finite element models of both structures were constructed by utilizing the SAP2000 software in this study. These models were calibrated by a number of non-destructive tests carried out on the stuctures including rebound hammer, ultrasonic pulse velocity, infrared thermography, ground penetrating radar and ambient vibration tests. Models were used to carry out time history and response spectrum analyses; critical structural elements in both structures that are expected to sustaine damage were then identified based on the results.

KEY WORDS : Historical monuments, seismic vulnerability, dynamic behaviour

1. INTRODUCTION

The earliest documents that mention the cathedral of St. Nicholas in Cyprus go back to 1300 (Enlart, 1987). This era corresponds to the first period of Lusignan rule in Cyprus, during which Frankish nobles were very powerful and the island was economically prosperous (Solsten, 1991). This wealth was expectedly reflected to the quality of architectural landmarks produced in that period. St. Nicholas Cathedral is one of the finest examples of these architectural landmarks. The style of this Cathedral heavily corresponds to the Rayonnant style in Gothic architecture that was developing in Europe during that very same period.

St. Nicholas Cathedral was the location for the coronation of the Lusignan kings as Kings of Jerusalem after they had been crowned in Nicosia (Cyprus) as Kings of Cyprus. According to Enlart (1987), it is because of this functionality that St. Nicholas Cathedral imitates architecturally Rheims Cathedral of France. In 1472, St. Nicholas Cathedral was the scene of the King James of Cyprus's marriage to Catherine Cornaro, the god-daughter of a Venetian senate member. In July 1473, this very same king was buried in the St. Nicholas Cathedral.

St. Nicholas Cathedral is a structure with a plan area of 24m - 50m, and a height of 29m. It consists of a nave of seven bays ending in a polygonal apse flanked by aisles ending in apsidal chapels of similar shape. The last bay of the North aisle communicates with a sacristy composed of two roughly rectangular rib-vaulted bays (Figure 1). Enlart (1987) indicates that from this sacristy, one could go down into a cistern. In 1571, with Cyprus entering the Ottoman rule, a minaret was added to the St. Nicholas Cathedral and it has been in service as a mosque since then.

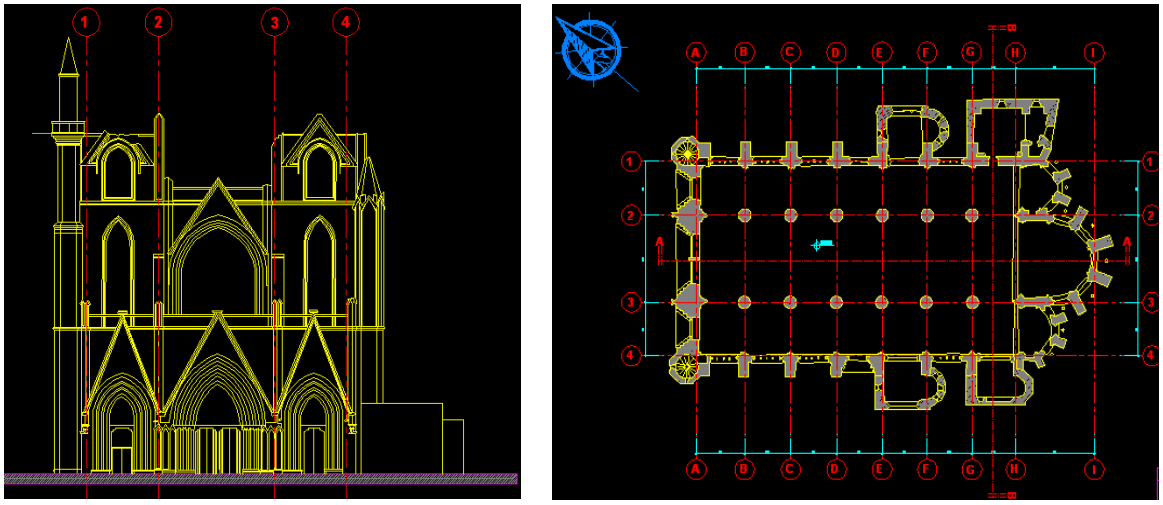

Figure 1: The front façade and plan views of St. Nicholas Cathedral

The Cathedral being located at the Southeastern part of the island, due to its proximity to the eastern arm of the Cyprus Arc (main seismic source for the island), sustained severe structural damage caused by earthquakes a number of times throughout its history. According to Enlart (1987), the flying buttresses and roof structure of St. Nicholas suffered severely in 1546 and 1568 earthquakes. Ambraseys (1963) mentions that due to an earthquake in December 1735, part of the cathedral fell and buried under its ruins over 200 people. According to Imhaus (2007), the earthquake of 1941 caused further damage to the roofing structure of St. Nicholas Cathedral to such degree that a number of strengthening measures had to be taken to stabilize the structure over the period of 1951-1974. Even from this rather short account of history of the St. Nicholas Cathedral, it is obvious that this structure is one of the finest, unique landmarks of the island with a very important place in the Cypriot culture. But with documents indicating repetitive severe damage, seismic vulnerability of the structure is evident as well.

St. Mamas Church of Morphou, Cyprus is a comparatively younger structure that dates back to the 16th Century (Enlart, 1987). The era in which St. Mamas Church was constructed corresponds to the latest phase of Lusignan architecture on the island (AC. 1360 to 1581). This phase is characterized by poor building quality, a reflection of impoverished conditions caused by Genoese aggression. Any stimulating contacts with Western Europe appear to have ended and the repertory of construction became almost exclusively insular in this phase (Kyprou, 2002). However still, St. Mamas Church is considered to be one of the finest examples of the Franco-Byzantine type architecture on the island (Kyprou, 2002), which combines features of Byzantine (the dome) and Gothic (the pointed arch) characteristics in it (Figure 2b).

Structurally, St. Mamas Church belongs to the type of three aisled basilica with a dome (Kyprou, 2002). It is a single-story structure with a plan area of 19m - 8m and a height of 7.5m that utilizes 1m thick perimeter walls together with a system of cylindrical vaults and a spherical dome (Figure 2). The aisles are separated by two colonnades of five columns. In the late 19th Century, a bell tower was added to the structure at the Northeastern corner as well as the porticoes on the north and west sides of the structure (Enlart, 1987). From the search of historical records, no mention of previously sustained earthquake damage could have been found, although Ambraseys (1992) indicates that the Morphou region was shook severely by the two rather recent earthquakes of 13 June 1933 and 6 November 1968.

The main objective of this study was to assess current states of these structures by carrying out tests to characterize their construction material properties, soil properties and later based on this information to develop accurate structural models of them that would allow identification of their critical structural elements under possible regional major earthquakes of future. In the light of results of this study, developing strategies that would enable protection of St. Nicholas Cathedral and St. Mamas Church against seismic damage is the main future goal.

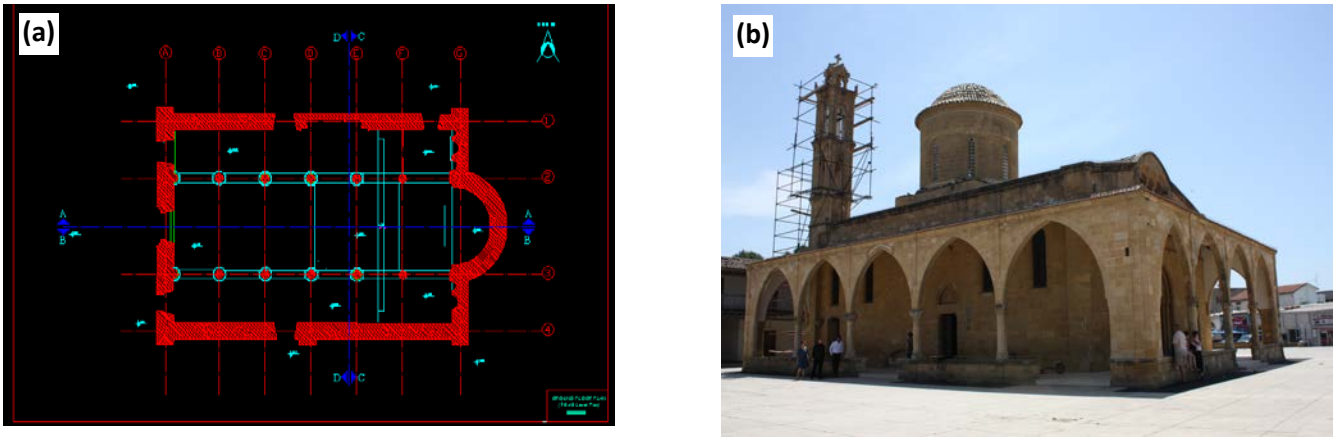

Figure 2: St. Mamas Church (a) plan view (Northern and Western porticoes are not included to the drawing), (b) picture of Northern and Western facades of the structure.

2. NON-DESTRUCTIVE TESTING

St. Nicholas Cathedral is made up of local calcarenite entirely. In this study, variability of mechanical properties of this construction material throughout the structure was evaluated by carrying out a number of non-destructive tests including rock hammer, infrared thermography, and ground penetrating radar tests etc. Due to the considerable age of this structure as well as construction material's being a natural stone, huge variability in measured mechanical properties was anticipated.

Rock hammer test was applied to the interior and peripheral columns of first and second floors. The instrument utilized for this purpose was an L-type rebound hammer with an impact energy value of 0.74nm. From each of first floor interior columns, 20 readings were taken as well as from exterior surfaces of first and second floor columns (For detailed readings please refer to Cagnan, 2010[a]). Detailed inspections at the structure revealed that the level of deterioration due to weathering of exterior surfaces was considerable in comparison to interior surfaces. The structure's proximity to the coastline, detected drainage problem that increases moisture level at the structure,

accumulated pigeon droppings, considerable temperature differences between day and night are all the main parameters contributing to the high level of deterioration observed. Inside of the structure, however, was repeatedly white washed by application of gypsum layers to the masonry since the structure was started to be used as a mosque. Although based on the initial inspections, it was anticipated that rock hammer readings obtained from exterior surfaces would be lower than interior surfaces, results do not indicate such. This is suspected to be the result of application of gypsum layers repeatedly on to the interior surfaces. Results indicate that Southern façade flying buttresses have higher surface hardness values (despite of being severely weathered) in comparison to those of Northern façade; this is believed to be caused by lower level of moisture on the Southern surfaces.

Infrared thermography tests were conducted on the roof structure and the internal columns of the cathedral to examine existence of cracks on elements of the structure that are difficult to reach otherwise and to examine level of moisture uptake at columns through foundation with capillary action. A map of moisture level of masonry throughout the building was tried to be developed as moisture accelerates its deterioration. No noticeable temperature variation was detected over the roof structure. However infrared camera readings consistently decreased as moved from top towards bottom of internal columns indicating existence of moisture up take, especially nearby Northeastern corner of the structure where the cistern is believed to exist (For detailed readings please refer to Cagnan, 2010[a]). However it should be underlined that moisture level at the flying buttresses and peripheral walls of 2nd floor is much higher in comparison. This is caused by blocked drainage system of the structure that consists of channels running over the flying buttresses. A problem that is needed to be addressed more urgently than the moisture uptake problem through the foundation.

The ground penetrating radar surveys were conducted both on the floor and interior columns of the structure with the objective of identifying any underground structure below the cathedral and to assess the interior of columns, determine existence of any internal cracks. The ground penetrating radar survey conducted on the floor revealed the location of the cistern at the Northeastern corner of the structure as mentioned by Enlart (1987). Although no interconnecting beams were found between columns (hence foundation type is pad foundation), along axe 3 of the structure, remains of what is believed to correspond to the church of St. Sopia were identified in the form of repetitive diffractions (Figure 3). Surveys conducted along each column element revealed several heterogeneities that were anticipated given the size of the elements however in order to associate these with cracking further tests must be conducted such as endoscopic tests. Both surveys were performed by a 400 MHz antenna that has a moderate resolution up to 5m. For survey of columns, a higher frequency unit could not be used that would have provided higher resolution as diameter of these elements are 1.6m.

In addition to documenting variability of mechanical properties of the masonry throughout the structure and to detecting local weaknesses such as internal cracks, voids; the non-destructive tests carried out had the purpose of determining compressive strength and modulus of elasticity values for the local calcarenite. However to achieve this, rock hammer test results had to be calibrated for the material under consideration. This was done based on results of laboratory tests conducted on 5cm x 5cm sample cubes obtained from the St. Nicolas Cathedral (Cagnan, 2011) and ambient vibration tests conducted by Votsis et al. (2011) on St. Nicholas Cathedral. Based on these test results, an average compressive strength value of 12 MPa, an average tensile strength value of 1.2 MPa (1/10 th of compressive strength) and an average modulus of elasticity value of 610 MPa was decided to be used in this study. A density value of 1.7 gr/cm^3 was utilized for the calcarenite.

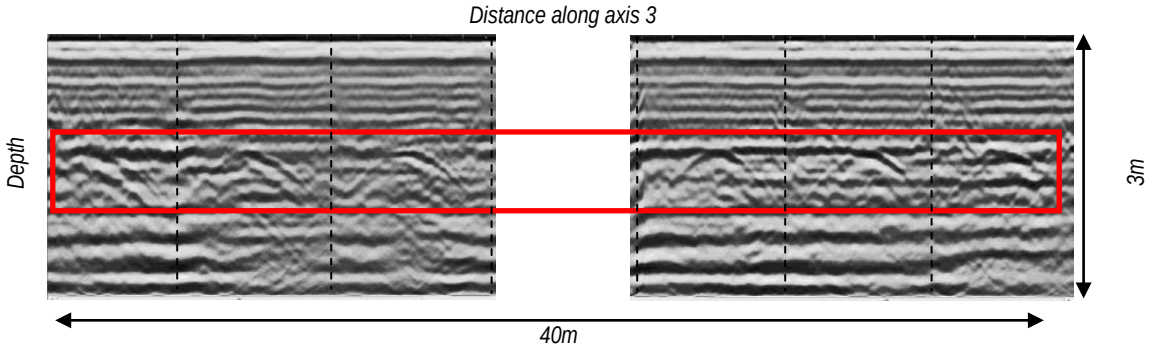

Figure 3: Ground penetrating radar survey results along axis 3 (the reader should refer to Figure 1 for the exact location of axis 3). Red rectangle encloses the diffraction like events representing the underground structure detected. Black vertical lines indicate locations of axes B-E and F-G from left towards right. The distance between axes E and F could not be surveyed because of obstructions caused by permanent fixtures of the structure.

Rock hammer test was applied to the internal columns and peripheral walls of St. Mamas Church by following the same scheme as was followed in the case of St. Nicholas Cathedral. According to the results (for detailed readings please refer to Cagnan, 2010[a]), the middle columns of axis 3 (F3, E3, D3, C3) have relatively higher mean strength values in comparison to the rest. This can be one reason for the observable cracking on columns D2, E2, F2 (supporting the dome above) whereas their mirror image counterparts on axis 3 being crack free. The rock hammer test results obtained for peripheral walls (both interior and exterior readings) had similar average and coefficient of variance values as those obtained from the interior columns.

The roof structure of St. Mamas Church is in a rather deprived state due to high moisture level caused by malfunctioning drainage system. As presence of water accelerates deterioration of masonry, variations in moisture content were documented by employing the infrared thermography technique (for detailed readings please refer to Cagnan, 2010[a]). Results obtained indicate positive temperature gradients along the height of internal column elements suggesting moisture intake from the foundation of the structure through capillary action in the case of St. Mamas Church as well. However the lowest of all temperature measurements taken corresponded to the two side aisle vaults. On these vaults, severe discoloration was observed; the measurements obtained are the proof that these discolorations are not just stains but due to high moisture content of the masonry at these locations.

With the conducted ground penetrating radar surveys, numerous archeological remains were detected throughout the plan area of St. Mamas Church. These were found to exist at two main depth levels: (i) 0.75-1.25m and (ii) below 1.5m, probably corresponding to the early Christian and Byzantine church remains that are believed to exist at the same location as St. Mamas Church (Enlart, 1987; Figure 4). Existence of such remains/cavities may give rise to settlement problems; hence the observed difference in behavior of axes 2 and 3 columns can also be attributed to differential settlement caused by these detected remains/cavities. However, it should be underlined that remains detected are not localized along axis 2 only but rather distributed throughout the whole floor area.

In case of St. Mamas church, the construction material is again local calcarenite but in comparison to the material used at St. Nicholas Cathedral has a higher sand content and lower surface hardness. Based on the rock hammer test results, uniaxial compression tests conducted on the samples taken from St. Nicholas Cathedral and ambient vibration tests conducted at St. Mamas Church, a compressive strength value of 10MPa, tensile strength

value of 1MPa (assumed to be 1/10 of the compressive strength) and modulus of elasticity value of 425 MPa was used in the analyses phase of this study for the St. Mamas Church. For columns D2, E2, F2, these values were further reduced by 20% as a reflection of observed surface hardness and porosity variations. A density value of 1.7 gr/cm^3 was used throughout the whole structure.

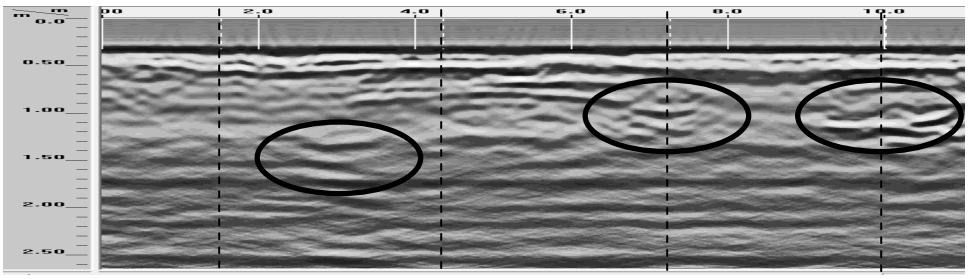

Figure 4: Ground penetrating radar survey result along axis 2. Horizontal axis represents distance along axis 2, vertical axis represents depth. Dotted black lines represent locations of columns B2, C2, D2, E2 from left to right respectively. Black ellipses enclose identified remains along axis 2.

3. MODELLING AND DYNAMIC ANALYSES

Based on the drawings obtained from Famagusta Municipality and measurements taken on site (Figure 1), a 3 dimensional FE model of the St. Nicholas Cathedral was developed. This model uses 3 dimensional solid elements for the peripheral abutments, internal columns and the western façade peripheral wall that reaches 4m thickness in between the three entrance doors and 2 dimensional shell elements for second floor and first floor vaults, Northern, Southern and Eastern façade peripheral walls, flying buttresses and the towers. In the model, the peripheral walls and internal columns were fixed at the base and all openings such as doors, windows, flying buttress piercings were accurately included. The mesh size was kept almost constant throughout the structure (and was alike the actual stone size at the structure) except from around the openings which had to be varied to match the required geometry. The model consists of 17,600 shell elements and 7100 solid elements and was implemented in the SAP2000 software (Computers and Structures, 2011).

In order to determine the soil conditions at the St. Nicholas Cathedral site, shallow seismic surveys and geotechnical drilling were performed within the scope of this study (Cagnan, 2010[b]). Seismic surveys were conducted by a receiver cable and 48 geophones positioned with 1m interval along the Western façade of the structure in order to obtain 2 dimensional P- and S-wave velocity profiles up to 30m depth along this cross section. Geotechnical drilling took place at the South western corner of the structure until 30.2 m depth was reached. At every 1.5m, SPT-N (Standard Penetration Test) values were also determined and disturbed samples were taken to be able to classify the formations below the structure. Results indicate that the specific V_{s30} (average shear wave velocity up to 30m) value corresponding to the site of interest is 560 m/s. Cagnan and Tanircan (2010) suggested that for the site of St. Nicholas, the peak ground acceleration level corresponding to a return period of 475 years is 0.29g. This peak ground acceleration value, together with the V_{s30} value of 560 m/s and the Eurocode 8 suggested base response spectrum function was utilized to develop a site specific response spectrum for the St. Nicholas Cathedral. In the seismic behavior assessment of the structure, this developed site specific response spectrum was utilized. According to the response spectrum analyses results, a 475 year return period earthquake for 5% damping ratio would create tensile stresses not exceeding 0.3 MPa at internal columns and peripheral abutments. It is only at the flying buttresses and flying buttress-vault connections that tensile stress level exceeds 1.2 MPa (Figure 5). It is the out of plane bending of flying buttresses that is developing

tensile stresses in these elements beyond the assumed strength level. Results obtained are consistent with the previous earthquake damages sustained by the structure according to historical records and results of inspections and non-destructive tests carried out at the structure. Time history analysis was carried out using the developed model together with six different response spectrum compatible records selected from the Turkish strong motion database (Akkar et al., 2010) and the Italian strong motion database (Massa et al., 2010) as no acceleration records exists for the Famagusta region. The results obtained are in agreement with the response spectrum analyses results hence will not be discussed in detail because of space limitations.

In the developed model of St. Mamas Church, all structural elements were represented by shell elements. Thicknesses of these elements vary considerably throughout the structure, i.e. 1m for peripheral walls, 0.55m for internal columns, 0.35m for the vaults and the spherical dome. The dimensions of various structural elements were quite accurately obtained with the help of a laser scanning instrument; except for the vault and dome thicknesses. As accurate dimensioning would require causing damage to the structure, these thicknesses were assumed to be 0.35m in this study. The bell tower and the porticoes were not included into the model of the church explicitly as these parts were added 300 years later to the original church building and hence are structurally independent. The effect of bell tower was taken into account indirectly as additional mass at the Northeastern corner of the structure. All peripheral and internal walls were set fixed at the foundation level in the model.

Similar to the case of St. Nicholas Cathedral, the soil conditions at the St. Mamas Church site were determined by carrying out shallow seismic surveys and geotechnical drilling (Cagnan, 2010[b]). Results indicate that the specific V_{s30} value corresponding to the site of interest is 310 m/s. Cagnan and Tanircan (2010) suggested that for the site of St. Mamas Church, the peak ground acceleration level corresponding to a return period of 475 years is 0.28g. This peak ground acceleration value, together with the V_{s30} value of 310 m/s and the Eurocode 8 suggested base response spectrum function was utilized to develop a site specific response spectrum for the St. Mamas Church. With the response spectrum analyses, the most critical regions were obtained to be the internal colonnades and roof-drum connection regions for the St. Mamas Church. At these locations simulation results indicate a tensile stress level of approximately 1.4 MPa (Figure 6). As for the Morphou region as well strong motion records are deficient, records obtained elsewhere with similar response spectra were utilized in the time history analyses. These records (six in total) were selected from the Turkish strong motion database (Akkar et al., 2010) and the Pacific Earthquake Engineering Research Center strong motion database. As in the case of St. Nicholas Cathedral, results obtained from the time history analyses are comparable with those from response spectrum analyses hence will not be discussed here because of space limitations.

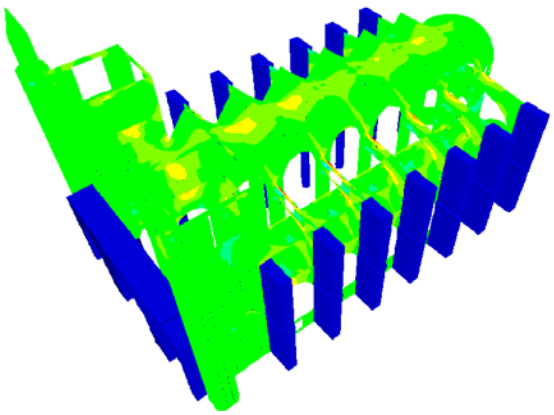

Figure 5: Stress distributions from response spectrum analysis for the three dimensional model of St. Nicholas Cathedral. Identified critical structural elements are Northern and Southern façade flying buttresses and flying buttress-vault connections. Yellow regions correspond to over-stressed (tensile stress) hence critical structural elements.

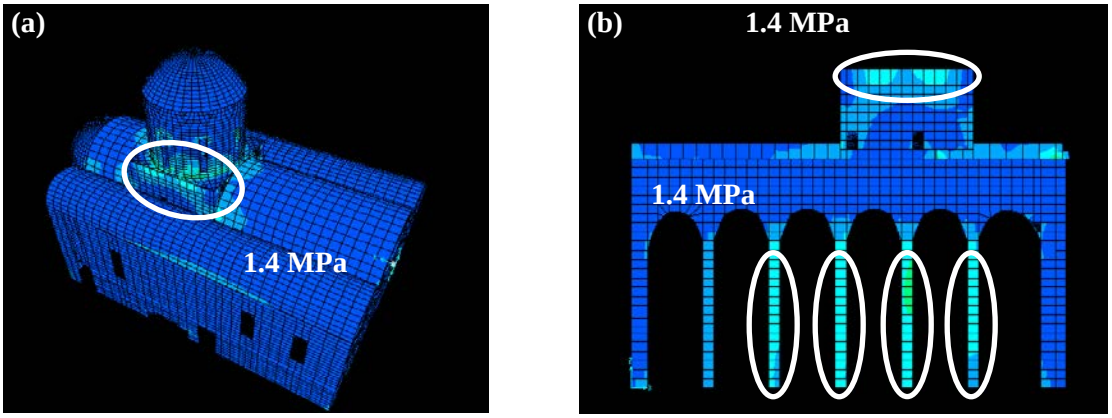

Figure 6: Stress distributions from response spectrum analysis for the three dimensional model of St. Mamas Church. Identified critical structural elements are internal columns and drum-lower roof connection points.

4. CONCLUSIONS

In this study, seismic vulnerabilities of two masonry historical structures in Cyprus with different architectural styles were assessed. Results indicate that under an earthquake loading with a return period of 475 years, both St. Nicholas Cathedral and St. Mamas Church can sustain critical structural damage. In the case of St. Nicholas Cathedral, simulation results are in agreement with the historical accounts of previously sustained earthquake damage. In the case of St. Mamas Church, results are descriptive of the crack pattern observed at the structure and also in agreement with the earthquake damage sustained by the structures of similar size and architectural style in the Balkan region. Obtained results clearly illustrate the necessity for the local and international stakeholders' immediate action towards preservation of these two unique structures.

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