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In situ investigation and stability analysis of Famagusta Churches

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ABSTRACT:
Famagusta was placed on the 2008 World Monuments Watch List of 100 Most Endangered Sites by the World Monument Fund. A joint collaboration between University of Minho, Eastern Mediterranean University (EMU) and the Municipality of Famagusta was established with the aim to analyze the stability of the Medieval Churches. After a brief inspection and visit of the site, the churches were selected for reporting and non-destructive testing: (a) St. George of the Latins; (b) St. George of the Greeks; (c) The Carmelite Church. Based on the photographic documentation and in situ testing, the present condition and required items in the conservation projects of the churches are addressed. The stability of one of the churches is detailed using collapse mechanism limit analysis and finite element model updating based on dynamic identification and push-over analysis.

Keywords: *Gothic churches, in situ evaluation, stability, seismic analysis*

1 INTRODUCTION

The city of Famagusta, located in North-East Cyprus, Figure 1a, has been over many centuries at the crossroads between the West and the East, and has played a pivotal role between the Christian and Islamic Worlds. The heritage treasures of this city combine medieval Christian churches and some impressive city walls, among other treasures. Famagusta, once known as the richest city in the world, is now threatened by earthquakes, abandonment and neglect. Due to the severe state of deterioration it was placed on the 2008 World Monuments Watch List of 100 Most Endangered Sites by the World Monument Fund.

After a brief inspection and visit of the site, three churches were selected for reporting and non-destructive testing, see Figure 1. Preliminary recommendations have been issued, based on the observed damage and condition. For the Church of Saint George of the Latins, detailed structural analysis has been carried out, including model updating based on in situ dynamic identification, collapse mechanism limit analysis and push-over non-linear analysis. It is noted that the limit analysis has been carried out as predictive, before the push-over analysis, and good agreement was found. It is also noted that the church analysed seems unsafe with respect to the local seismic hazard.

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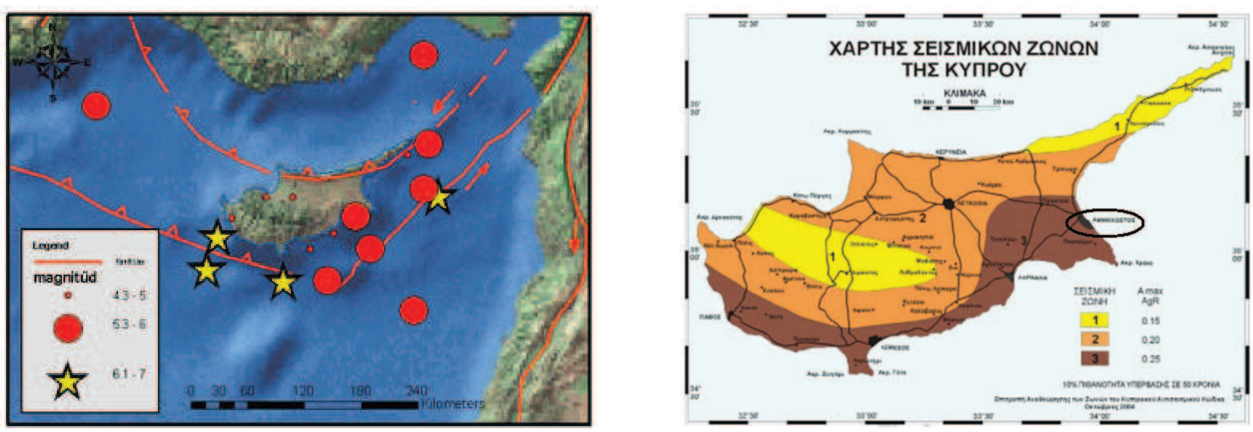
(a) (b)

Figure 1. Location of: (a) Cyprus Island and Famagusta; (b) Churches studied in the walled city

2 LOCAL SEISMICITY

Cyprus is located in a tectonically complex zone where three continental plates assemble: African plate to the south, Eurasian plate to the north and Arabian plate to the east. The Alpine-Himalaya belt is the second most intensive seismic zone of the earth, where the earthquakes that occur represent about 15% of the world seismic activity, and Cyprus is located in this region, on the southern side of the Anatolian Plate. Its seismicity is attributed to the "Cyprus Arc" which is the tectonic boundary between the African and Eurasian plate, with many epicenters reported. According to historical references and archaeological findings, Cyprus has been struck by strong earthquakes in the past, which destroyed and damaged towns. Sixteen earthquakes with intensities of VIII (on modified Mercalli scale) or higher occurred between the years 26 BC and 1900 AD. Two of them had big impacts in Salamis (today's Famagusta) and destroyed the whole town (in 76 AD and in 332 AD). After 1896 more accurate data started to be collected, and since then more than 400 earthquakes had epicenters on Cyprus and the surrounding region, with 14 of those causing severe damage as well as victims, see Figure 2a. Two earthquakes caused damage in Famagusta (1924 and 1941), with magnitudes about 6.0.

According to the Seismic Hazard Map of Cyprus, Figure 2b, the maximum peak ground acceleration (PGA) on rock for Famagusta is about 0.25g. Famagusta is located over Terrace deposits, mainly formed by Calcarenites, sands and gravels, which is likely to increase the hazard.



(a) (b)

Figure 2. Seismiciaty in Cyprus: (a) Distribution of catastrophic and damaging earthquakes on Cyprus between 1896 and 2000; (b) Hazard map in CYS EN 1998-1:2005, 2007

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The church is located inside the city walls, and it was probably built before the city was walled because it was a fortified church. Although in a ruinous state, it is an impressive example of Gothic architecture with excellent masonry, compact proportions and rich stone carving decoration. The church still preserves its northern half, the lower section of the apse and a part of its south side. The church is from the 13th century and is recorded as the oldest building in Famagusta. Its layout is quite simple, as a single-aisled building with four groin vaults that are supported by a grouping of three thin columns located in the north and south walls. Like in most Gothic churches, it has large and high windows, which used to have carved stone decoration. The church has some impressive gargoyles depicting human figures and winged dragons. A survey of the church was carried out [1] using a laser distance meter to confirm existing drawings [2], see Figure 3. The church remains are about 25 m long, 15 m wide and 17.5 m high. Subsequently, a visual inspection, dynamic identification and sonic testing were carried out.

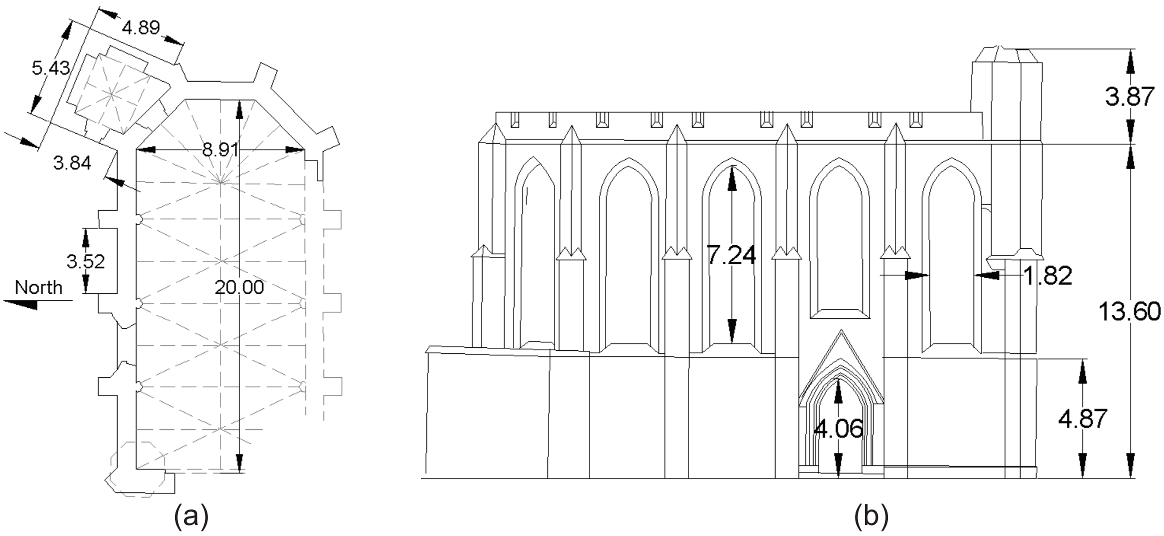


Figure 3. Geometrical survey: (a) in plan; (b) elevation

3.1 Visual inspection

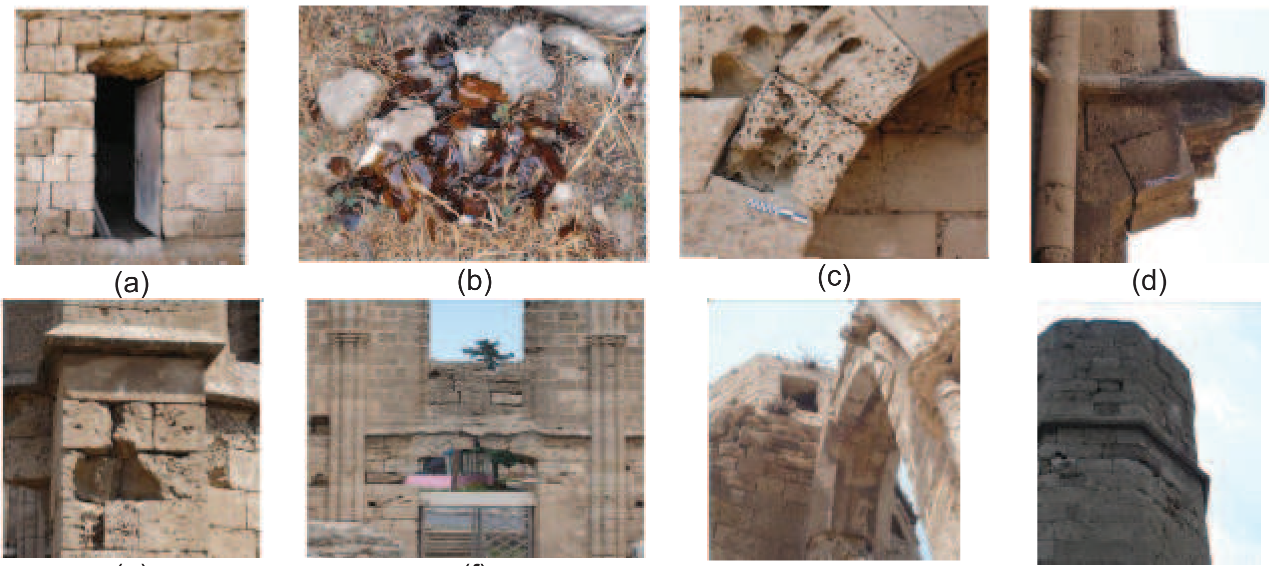
According to the inspection works carried out [1], the present condition of the church seems not to differ significantly from the condition around 1940, Figure 4. Severe deterioration of the stones is reported in drawings from 1882 and several stones have been replaced in the conservation works undertaken around 1940. The present condition is further detailed in Figure 5.

3.2 Dynamic Identification tests

Dynamic identification combines vibration testing techniques and analytical methods to determine modal parameters of structures, such as frequencies, mode shapes and damping coefficients. Those parameters are helpful to understand how a structure responds to dynamic excitations, such as earthquakes or winds, and to calibrate the computational model of a structure. With this purpose, output-only modal identification techniques were applied and the structure was excited with ambient vibration. Three accelerometers with 10 V/g sensitivity and able to measure 0.07mg were used to measure accelerations and they were connected to a laptop by a 24-bit resolution data acquisition system using USB cable connection. All the measurements were carried out using the natural vibration of the structure, over long periods of 10 minutes, with a sample rate of 200 Hz, and the data was processed using Stochastic Subspace Identification (SSI) methods. The ambient temperature and relative humidity were also measured while the dynamic test was performed, but variations were small.

(a) (b)

Figure 4. Analysis of historical photographs: (a) situation in 1940s vs. current condition; b) new (lighter) stone used in 1940s



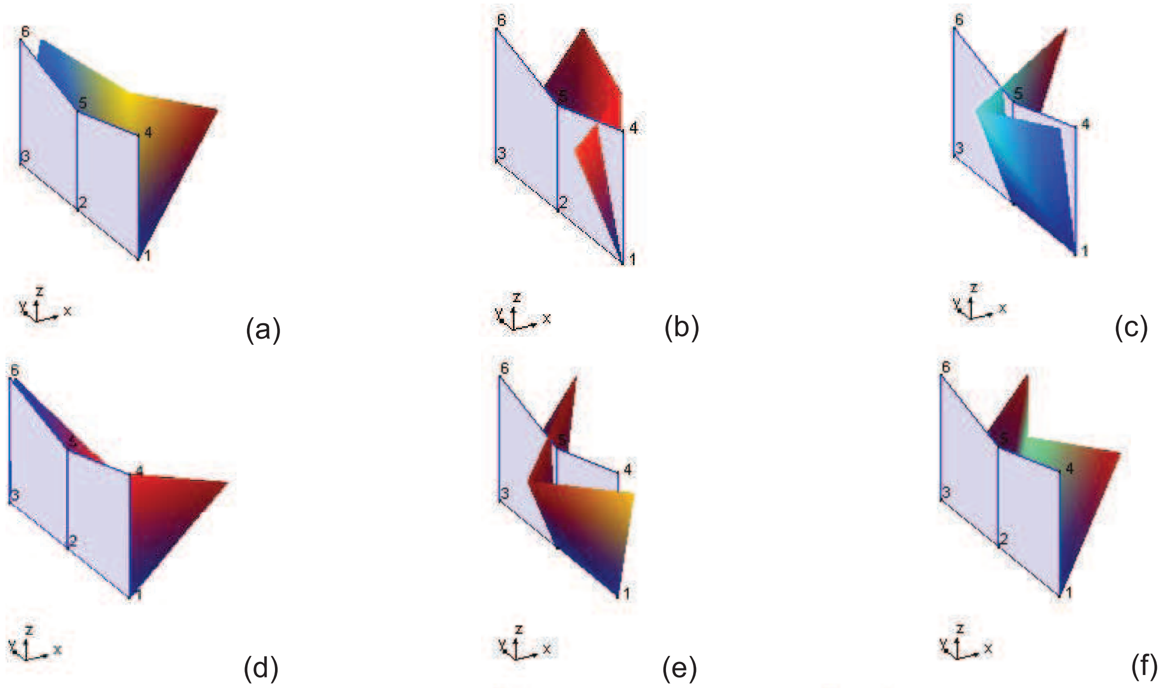
(a) (b) (c) (d)
(e) (f) (g) (h)

Figure 5. Details of current condition of the church: (a,b) litter / possible misuse of one room (sacristy); (c) severe stone deterioration; (d,g) loose stone elements, which must be consolidated or removed; (e) inefficient buttresses due to stone deterioration; (f) highly corroded reinforced concrete lintel in main door; (g,h) a crack / rotation of the tower, possibly due to a previous earthquake / foundation problems

The measurements were carried out mainly at three points in the North façade, close to the top of three buttresses [1]. The natural frequencies of the structures which were found are well spaced and their values range between 2.6 to 18.0 Hz. The standard deviation is low, indicating that they were well estimated. The configurations of the mode shapes are mainly out-of-plane modes, as expected, due to the unconstrained walls of the church ruins. The first six modes, and their measured frequencies and damping coefficients are presented in Figure 6.

3.3 Sonic testing

Sonic tests are based on the propagation of elastic waves across solid mediums, with frequencies ranging from 0.4 to 10 kHz. Hence, knowing the distance between two points in the medium (the wall) and by measuring the travel time, it is possible to calculate the sonic velocity. Two types of sensors were used, namely a hammer for impact transmission and a receiver (an accelerometer) for reading. This technique can be used to locate potential areas in the structure with damage, control the efficiency of injection works for walls consolidation and qualitatively assess wall's morphology by correlating its results with other types of non destructive tests (NDT).

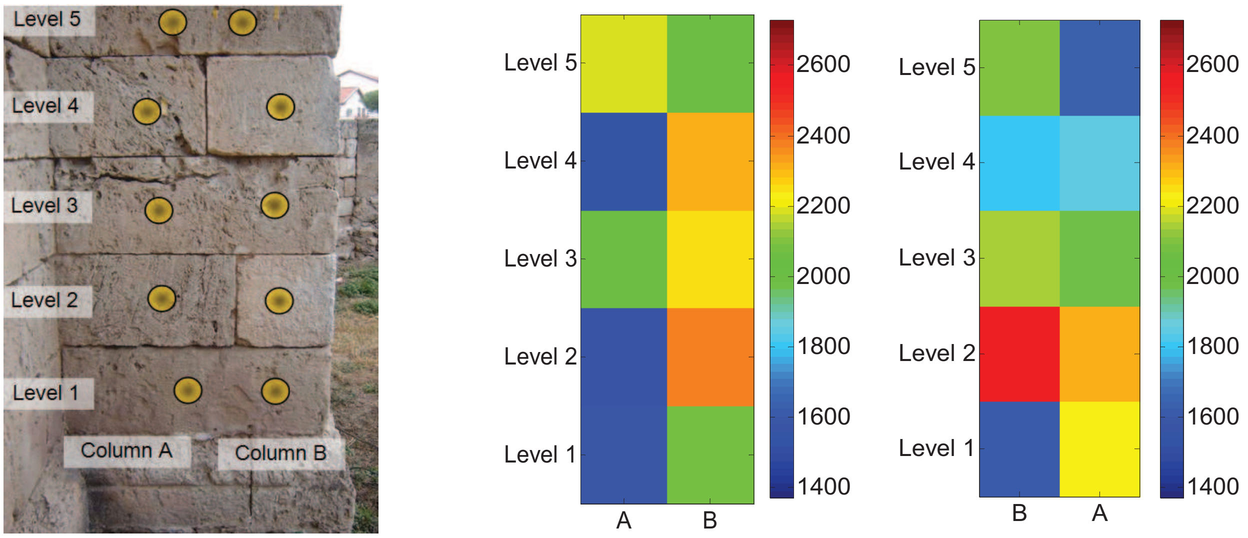


Modes	Frequency Values [Hz]	Frequency Standard Deviation [Hz]	Damping Values [%]	Damping Standard Deviation [%]
1	2.57	<0.01	1.04	0.38
2	3.14	0.01	1.05	1.02
3	3.95	0.06	0.55	0.57
4	4.06	0.02	0.58	0.14
5	5.26	0.02	0.85	0.16
6	5.61	0.02	0.77	0.21

(g)

Figure 6. Modal identification: (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode; (e) 5th mode; (f) 6th mode; (g) frequencies and damping coefficients

One calibration stone block and two buttresses thickness were tested [1]. The buttresses, one in the north façade and one in the south façade, were chosen to evaluate their internal condition, to determine if there are internal voids, different density materials or if repair works occurred in the recent past. The average value for the sonic velocity of the stone block was 3033 m/s, with a Coefficient of Variation (CV) equal to 5%. On each of the buttresses two vertical columns (denoted as A and B) and five horizontal levels were tested (10 points per column), see Figure 7a. The velocity results are illustrated in Figure 7b for the north buttress, where the sonic velocity ranges from 1400 to 2400 m/s and the average value for column A and B are 1597 and 2249 m/s, respectively. The outer points of the buttress (column B) have higher velocity than the inner points (column A), indicating that the stones in the outer column were probably replaced by new ones in the recent past, while the internal part of the buttresses are in worse condition. Concerning the south buttress, small differences were found between the velocity values. Ranging from 1400 to 2600 m/s, the average values for A and B were 1923 and 1996 m/s, respectively, see Figure 7c. The values indicate that the internal condition of the buttress in the two columns (internal and external) is similar.



(a) (b) (c)

Figure 7. Sonic test results: (a) location of measured points; (b) North buttress; (c) South buttress

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These two churches were also surveyed, visually inspected and dynamically tested[1]. Here, the inspection results are only briefly reviewed.

4.1 St. George of the Greeks

The Church of Saint George of the Greeks is the largest Frankish Orthodox church in Cyprus measuring 37.5 × 20.5 m^2. It is dated with some certainty to the second half of the 14th century. The building is an interesting example of a Greek Orthodox church with French Gothic architectural features. Unfortunately all that is left of the building are its east end – its central and side apses with their pointed domes – the nave's south wall and the lower part of the west end. The church is built with square sandstone blocks and it is thee-aisled with two rows of columns. The dome sits on the square space formed by the second and the third column of each row and the building has groin vaults. In the east the three aisles end in semi-circular apses. The roof has supporting pillars that bear the weight of the building's central aisle. The church's windows are simple and pointed whilst the entrances are adorned with carved relief decoration. Attached to the church's south side is the ruined small church dedicated to Saint Symeon.

The interior of the church was adorned with wall paintings but most of them were destroyed after the dome and the upper part of the building collapsed. Some fragments survive in the apses (depicting the figures of saints) but are exposed to the elements and are severely weathered.

Figure 8 again indicates that the present condition of the church seems not to differ significantly from the condition around 1940. Some aspects to be considered in a conservation project are given in Figure 9.

4.2 The Carmelite Church

The church of St Mary of the Carmelites is situated in the northwest corner of Famagusta. Because the Carmelites originated from the Carmel Mountains of Syria, this area became known as the Syrian quarter of the city. The church was built in the 14th century as the church of a monastery. It has a single nave of four bays and a three-sided apse. In the second bay, two small chapels were added. The roof had ribbed vaults, and the exterior walls were supported by buttresses. The tomb of Peter Thomas, who was the Pope's representative and the Patriarch of Constantinople, who died in 1366 was in this church. The walls of the church were covered in frescoes, and some of those are still (just) visible. Outside the west door, one can also see the remains of sculptures above the entrance. Recently, the tracery added by the British above the main door around 1940 collapsed, see Figure 10. Figure 11 again indicates that the present condition of the church seems not to differ significantly from the condition around 1940. Some aspects to be considered in a conservation project are provided in Figure 12.

Figure 8. St. George of the Greeks: Historical photographs (1939)

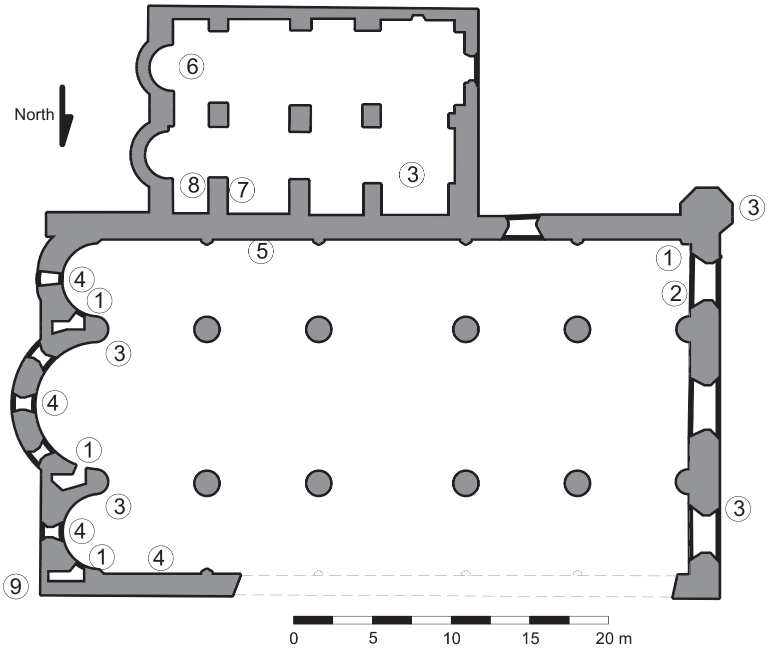

Figure 9. Recorded damages / possible remedial actions: (1) doors required to prevent free access; (2) moderate cracking; (3) need to verify if removal / consolidation of masonry / stones is needed; (4) needs protection of frescoes and engravings; (5) needs consolidation of window tracery; (6) needs consolidation of vault (roof possibly needs works to protect from rainwater); (7) needs consolidation of arch; (8) severe biological contamination; (9) needs consolidating flying arch

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The church of St. George of the Latins was further considered for stability analysis aiming at providing a first discussion on the seismic vulnerability of the Famagusta churches. For this purpose, collapse mechanism limit analysis and advanced non-linear analysis were carried out, and are detailed next.

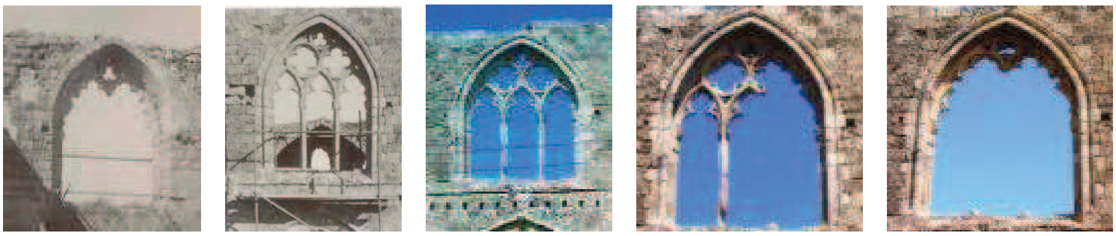


Figure 10. Window tracery above the main door

Figure 11. Historical photographs (1940, 1941), showing conservation works and the deficient condition of the church

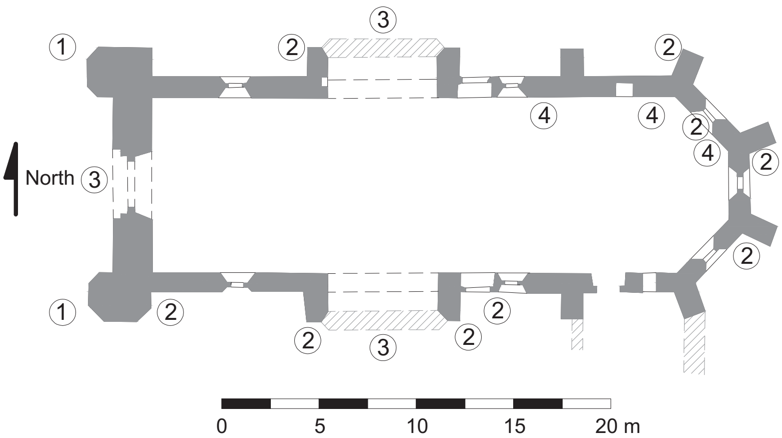


Figure 12. Recorded damages / possible remedial actions: (1) base of the towers exhibiting severe stone deterioration; (2) voids in the masonry; (3) possible elements to remove; (4) protection needed for frescoes and engravings

5.1 Collapse mechanism limit analysis

The use of limit analysis to analyze complex structures arose in Italy [3]. Several experimental and theoretical studies, carried out after important earthquakes, demonstrated that the behaviour of historical constructions differs from the usual continuum or linear elastic analysis. Collapsing configurations for structures with the same typology were gathered in an abacus [4]. This abacus is applicable for housing, churches and bell towers. Examples of failure mechanisms are out-of-plane rotation of load-bearing masonry due to lack of orthogonal connections or masonry expulsion.

For the structure under investigation, the macro-elements were defined according to the damage reported. The next step was to identify the most probable mechanism. In-plane mechanisms were disregarded due to lack of confinement in the structure. Despite the thickness of the wall, the arch effect was disregarded, as well as the bending of the horizontal strips. Thus it is expected that the results obtained are lower bounds. It is further noted that this analysis was carried out before any push-over analysis, as it was intended to use it as validation of the limit analysis approach.

The result obtained from the application of kinematic models is a load coefficient c:

$$c = a / g \quad (1)$$

where a is the ground acceleration and g is the gravity acceleration ($9.81 m/s^2$). The load coefficient is the mass multiplier that activates the local failure mode. The seismic safety of the structure is given by the lowest coefficient of all possible mechanisms. The kinematic approach also allows one to obtain the path of a reference control point, or the capacity curve, allowing one to assess safety in terms of displacements, see [4] for details of application to this structure. Figure 13 shows the six different collapse mechanisms considered for limit analysis. The minimum load coefficient obtained is 0.11 for the 2nd mechanism shown, which is overturning of the tower outwards and along the nave direction. The other load coefficients vary between 0.12 and 0.21.

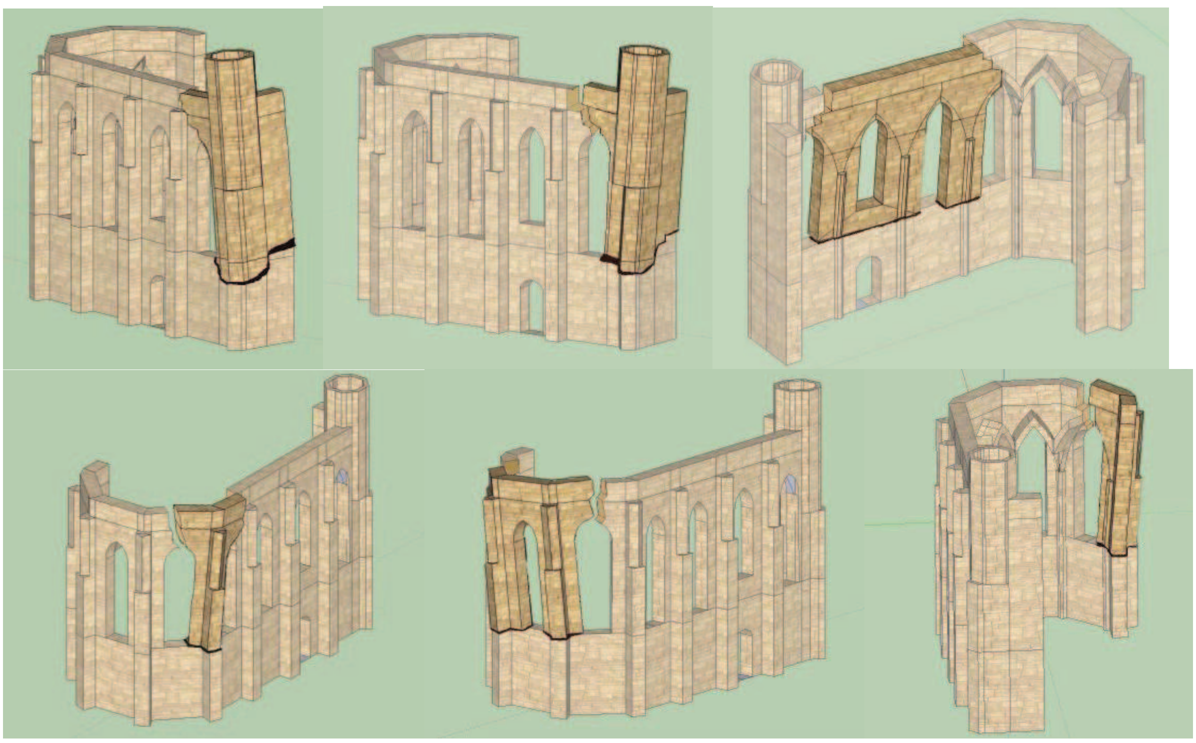


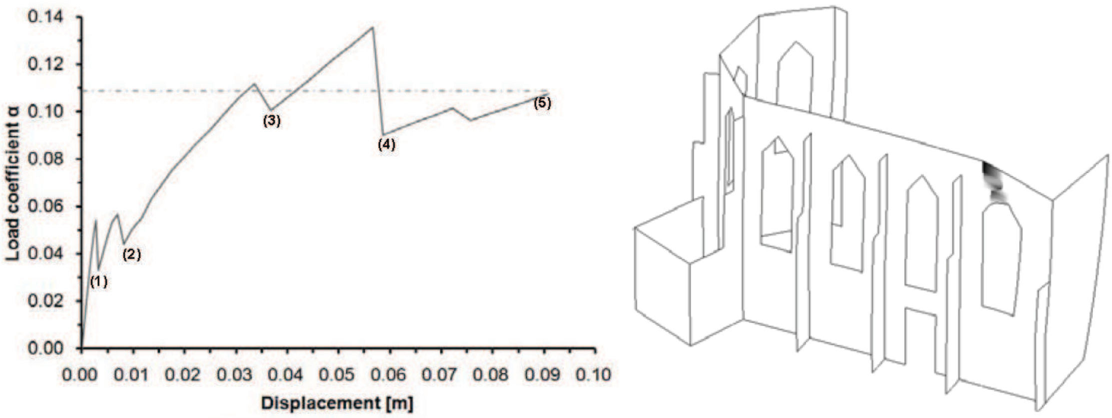
Figure 13. Collapse mechanisms considered for limit analaysis

5.2 Push-over analysis

The non-linear static analysis of the church, was preceeded by the defintion of a finite elment model based on the geometrical survey and the dynamic identification results. 3D solid elements were disregarded because they have a high computation cost and dynamic time integration analysis is to be carried out in a near future. Shell elements were used instead and several different models were tested, aiming at minimizing the difference between the measured frequencies and mode shapes, and the corresponding values in the model, see [5] for details. The model variations included the following:

(a) true inclusion of the vaults and upper part of the tower versus their replacement with additional masses; (b) inclusion of the cracks and the damaged areas visible in the structure. The model updating procedure allowed one to obtain an average error in terms of frequency of 2% and a reasonale MAC value.

The pushover analysis was carried out in the positive and negative main direction (parallel and perpendicular to the nave) and also in the principal axes of the in plan area. The values found are in reasonable agreement with the results found with limit analyis. See Figure 14 for the results of the pushover analysis paralell to the nave, for which limit analysis provided a load coefficient of 0.11.



(a) (b)

Figure 14. Push-over analysis along the nave: (a) capacity curve; (b) deformed mesh and cracking

6 CONCLUSIONS

This work presents the results of an in situ investigation and stability analysis of churches in Famagusta, Cyprus. The most relevant aspects to be considered in a conservation project were addressed. The main conclusions of the work regarding stability are: (a) limit analysis provided a good agreement with sophisticated non-linear push-over analysis, even for the case of church remains; (b) the structure analysed, and possibly the other structures investigated in situ, seem seismically vulnerable and further studies or remedial measures are necessary.

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