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STRUCTURAL ASSESSMENT AND RETROFITTING OF HISTORICAL CONSTURCTIONS: A CASE STUDY FROM ALBANIA

Abstract: A large portion of European and Albanian cultural heritage buildings is made of masonry. Many of them due to the decay and degradation of building material, aggressive environmental conditions, frequent seismic activity and various geological phenomena, as well as the lack of maintenance, are found to be in a very bad condition.

This paper includes application of recent research on the repair and strengthening of historical structures and provides a structural assessment of five historical mosques in Albania. Apart from visual inspection, terrestrial laser scanner (TLS) data are used to analyze the historical structures. The FEM analysis conducted in SAP2000 aims to investigate the structural behavior of the undamaged model under static and dynamic loads. As a result, possible practical solutions for the structural problems based on previous research and enhancement of the existing structural resistance are suggested.

Key words: heritage buildings, structural assessment, masonry structures, FEM, retrofitting, visual inspection, historical constructions

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1. INTRODUCTION

1.1. Overview of masonry structures

Masonry, together with timber, is the oldest building material and one of the widely used construction method around the world. It is still used nowadays due to low material costs, good sound and heat insulation, locally availability, aesthetics and simplicity of construction. The construction technique which consists of assembling bricks, stone or block units on top of each other, laid dry or bonded with mortar, is essentially the same as thousands of years ago, making it an easy, simple, very effective and useful method of construction. The structures that have still remained today, have proven to be durable and were erected without the requirement of any special skill.

As these structures were built when no detailed rules or regulations were applied, many buildings' current structural conditions do not satisfy the present guidelines. Natural disasters, aggressive environment and human intervention have caused extensive damage to these structures, many of which have been built with no considerations of these factors.

What makes a building and a structure historic is: its association with acts of historical importance and its oldness, which means the time that has passed since its construction is considerable. However, old is a relative term. In practice, it can be used to define a structure 50-100 years old. For ancient constructions, a building is considered to be historic if a few centuries have passed since the time it was built [1].

In 1989, Matthys and Noland estimated that more than 70% of the world's building inventory was made of URM. A large number of the total population, due to lack of economical resources, lives in non-engineered, sub-standard dwellings which are extremely vulnerable to collapsing. These figures have probably changed during the following years, but still remain high. Moderate or strong earthquakes may cause extensive damage or failure of these structures, killing many people and injuring thousands. Since demolishing is not a feasible option, strengthening and improving earthquake performance under cyclic ground shaking can be a good solution [2].

Due to their historical and architectural values, people nowadays require them to have a longer service life. These types of buildings need to be preserved for the next generations. Thus, there is a need for strengthening and retrofitting.

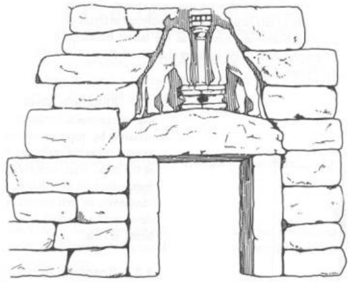
Strengthening, retrofitting, and repair of historical structures attempt to mitigate the associated hazards coming from natural disasters and deterioration of structure during time, and improve load resisting capacity as well as extend the service life of these structures.

1.2. Historical masonry constructions

Masonry construction is closely associated with the earliest civilization about 10 000 years ago. The first masonry material to be used was stone. Some of the earliest examples of permanent dry-stone masonry houses are found in Israel and date back to 9000-8000 B.C.

Nowadays, we are witness of great masonry structures which are inherited from the past such as Egyptian architecture with pyramids, 2800-2000 B.C., temples, palaces, bridges and aqueducts of Roman and Romanesque architecture 0-1200 A.D.; the 8800 km long Great Wall of China (14th century) Gothic architecture with cathedrals 1200-1600, etc. (Table 1) [3].

Table 1. Examples of historic constructions.

	
Egyptian pyramids (2800-2000 B.C.)	Lion Gate at Mycenae
	
Parthenon of Athens (5^{th} century B.C.)	Colosseum, Rome (1^{st} century A.D.)
	
Pont Du Gard (1^{st} century A.D.)	Hagia Sophia, Istanbul (6^{th} century A.D.)
	
Notre Dame de Paris, (14^{th} century A.D.)	Renaissance church domes, Florence Cathedral, (13 century A.D.)

2. LITERATURE REVIEW

Protection of cultural heritage has become an emerging problem in recent years. It rises as a necessity for elimination of structural problems or distresses that result from unusual loading and exposure conditions, inadequate design or construction practices. These distresses may be caused from overloading, natural disasters, foundation settlement, deterioration of materials, etc. Some of the reasons for the structures to be strengthened are [4]:

- To eliminate structural problems or distresses which result from unusual loading and exposure conditions, inadequate design or poor construction practices. These distresses may be caused by overload, fire, flood, foundation settlement, deterioration, possible earthquakes, etc.
- To correct design or construction errors,
- To resist exceptional or accidental loadings,
- To increase tensile, shear, flexural or compressive strength of structural members.

All interventions should be carefully planned and performed. Structural interventions have to assure structural compatibility with the original structure, keeping its original form as much as possible. Modified or new structural elements should not disturb the architectural appearance and aesthetics of the building [5].

Assessment of seismic vulnerability of historic masonry constructions is a very challenging task due to several uncertainties regarding mechanical properties and geometrical characteristics of the structure. Each masonry building is unique. Hence, it should be treated with special care. A correct structural analysis of the building requires a deep knowledge of building history and evolution, geometry, structural details, material properties, cracking pattern and masonry construction techniques. An accurate structural system can be developed by combining in-situ and laboratory test results. Generally, obtaining all the needed information for properly defining the numerical model is very difficult or even impossible. Because of this reason, simplified and iterative procedures of assessment are required.

Casarin and Modena conducted a seismic assessment of Santa Maria Assunta a Cathedral in Reggio Emilia, Italy. Evaluation of structural conditions was performed using different investigation and analysis methodologies (limit analysis and numerical approach) [6].

The suggested strengthening technique for Mihrimah Sultan Mosque, after a 3-D FEM analysis used to simulate static and seismic behavior of the mosque, of application of tie rods at both ends of the supported arches estimated a reduction of the compressive stress at the supports by 29-54% [7].

Lourenço et al, 2001, in their study, conducted assessment of seismic behavior of a basilica church, defining the most vulnerable parts and identifying the possible failure mechanisms. This analysis was carried out by 3-D modeling with geometric simplifications which provided the main characteristics and behavior of the structure. In some cases, since there are many uncertainties, the undertaken assumptions and simplifications can often mislead from the actual behavior [8].

In the last decades, there has been an increase number of numerical analysis tools for monumental buildings and case studies for analysis of structural response of historic masonry [9-11].

Assessment of the seismic vulnerability of historical masonry becomes even more challenging due to uncertainties of mechanical properties of masonry and geometric characteristics of the structure. In an analysis of Vicarius Palace in Pescia, using FEM analysis, the comparison of the expected seismic demand versus actual capacity of the palace indicated the insufficient resistive capacity of the building against earthquake [12].

In-situ analysis using the latest technological tools and a computer based analysis were utilized in order to determine a correct diagnosis for a 15th century monument that exhibited many structural deficiencies. Traditional strengthening techniques were found to be sufficient to achieve the desired structural resistance [13].

Another successful attempt to assess the conditions of stress and deformation before and after strengthening intervention through a FEM response spectrum based on Eurocode 8-1 is of St. Helen and Constantine Church in Piraeus, Greece, where combined techniques of grout injection, CFRP and steel tie rods were suggested to be used in order to rehabilitate and strengthen the church [14].

Other studies have been conducted by the author in the framework of assessment and preservation of heritage structures [15-25].

3. CASE STUDY

Albania is one of the oldest countries in Balkan Peninsula and Europe. There are many historical structures made of unreinforced masonry units (URM) that carry significant importance due to their unique, cultural, historical and architectural values. There are many historical monuments built during Ottoman period (1481-1912) in Albania still functional nowadays. The following structures were analyzed:

- **The Leaden Mosque** in Berat; a massive well-preserved mosque built in 1553-1554 and located in city center of Berat. It is composed of three parts totaling approximately 576 m^2: a 12 x 12 m squared plan prayer hall; the last prayer hall covered with four domes and a minaret rising 11 m above the ground. The stone and brick load-bearing walls are 1.05 m thick.
- **The Mosque of Preza**; built in 1547 on the castle walls and it is located in Preza district inside the archaeological area of the Preza castle. With a rough area of 135 m^2, it has a rectangular 7.30 x 19.00 m prayer hall built with rubble stones and 0.40 - 1.35 m thick walls.
- **Murat Beg Mosque** in Kruja; an adobe structure with a simple timber roof construction built in 1533-1534.
- **Mirahor Ilyas Beg Mosque** in Korca; built in 1496, was one of the most important buildings closely related with the urban development of the city. It is composed of

three parts, with an approximate area of 186m^2: a prayer hall with a square schemed plan of 11.75 m, the last prayer hall, and the minaret rising 26 m above the ground. The 1.25 m-thick load-bearing walls are made of stone and bricks.

- **Naziresha's Mosque** in Elbasan; built in 1590s, with an approximate area of 115 m^2, sits on a square plan of 10.70 x 10.70 m and has a cubic-shaped central hall of 8.70 m height. The load bearing system is comprised of a 0.35 m-thick-brick dome which rises 14 m above the ground and 1 m-thick stone walls. The minaret was damaged after an earthquake in 1920 which is why the upper section is missing [25].

Figure 1 - Locations of the studied mosques [25].

4. METHODOLOGY

The methodology used for this research is based on the assessment of visible symptoms that structural defects and distresses had caused throughout the structure. Then, a FEM modelling was done for the case when there was a need for further investigation of the damage state.

Geometric data acquisition was done by using a calibrated high-resolution digital camera (Nikon D90) firmly mounted on a laser scanner (Optech ILRIS 3-D Intelligent Laser Ranging and Imaging System) together with a Topcon GPT-3007 Total Station.

In order to perform the inspection efficiently, a simple inspection and assessment form has been adopted from Gülkan [1]. It consists of: general details of the structure (address, rough area, number of story, height), type of roof, material types, condition of load bearing elements, condition of the connections, earthquake hazard level, possible failure mechanisms, etc. At the end, recommendation is given whether to retrofit, demolish or conduct further analysis. Rating of severity levels is from none (contains no structural damage), light, moderate, severe to near collapse (a heavy damaged element or structure).

The outcome obtained from the visual inspection provides a general assessment of the current structural conditions based on the visual “symptoms”. Based on the final results, the next step to be taken is suggested. It is essential to choose the most compatible solution regarding the current structural conditions of the building, concerning about preserving as good as possible. This assessment procedure provides a general overview of the current structural conditions of the mosques. It provides the first step in preparing the analytical and computer model.

A FEM modelling was carried out in order to examine the behavior of the mosque under static and dynamic loads, to identify the weak locations of potential failure in the structure and to demonstrate the behavior of the structure based on as-built and assumed perfect geometry. Numerical analysis was done using SAP2000 v.15.0 software [26], based on Eurocode 8 (EN1998-1) [27], with consideration of the local earthquake code (KTP-N2, 1989) [28]. The elements and the materials were selected to obtain the most realistic simulation of the structure’s behavior.

The masonry walls and the dome were modelled using macro-modelling (masonry units and mortar layers are considered as a continuum, where masonry is isotropic, homogeneous and shows elastic behavior) with shell elements. The model consists of 9604 joints and 9563 shell elements (Figure 2).

5. ASSESSMENT RESULTS

5.1. Damage survey

The damage survey showed that all five mosques suffer from various types of cracks and other structural problems. It was observed that the most endangered mosque is Naziresha’s in Elbasan, whose actual structural conditions could be stated as “severe”.

Roofing system composed of domes or timber pitched roofs, exhibits a lot of deficiencies. Due to the improper isolation, in Naziresha’s, Mirahor Ilyas Beg and Leaden mosques spall of plaster is seen. In Murat Beg and Preza mosques deformed ceiling, rotten timber elements and broken tiles are observed. In Elbasan, over the rooftop vegetation growth is seen.

Structural conditions of the roof system of Mirahor Ilyas Beg Mosque in Korça seem adequate to carry static loads. However, there are found many structural cracks. Improper connection of the lanterns hanged at the top of the ceiling, in a later time after the dome was built, has caused extra local stress concentrations causing cracks around the connections (Figure 3).

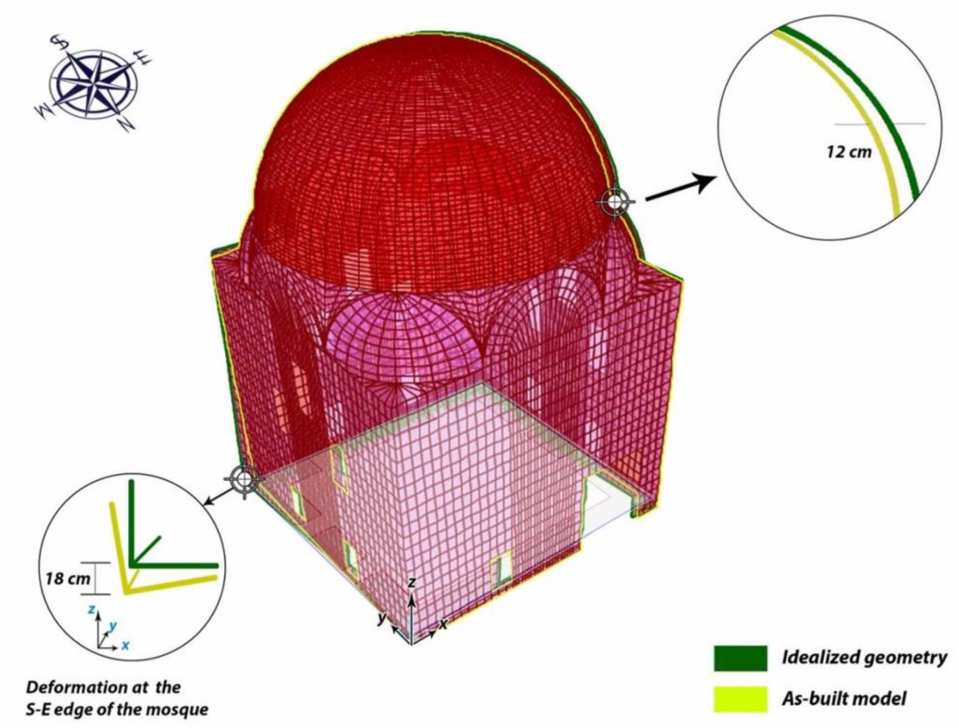


Figure 2 - FEM model of Naziresha's mosque.

Other structural cracks may have been caused by earthquake loads. Improper isolation of the roof system, high level of air humidity, leakage and penetration of rainwater inside the structure has caused dark moisture spots in the interior of the mosque.

Spall of plaster can be seen in some zones. There are also found cracks related to the old age of the building and amortization during time. Pendentives and arches suffer from the same problems. Thrust transferred from the dome loads may have exceeded their load carrying capacity.

According to assessment results, load bearing walls are the one that suffer most from damage and structural cracks. The most possible causes of these structural problems are excessive stress concentrations such as: compressive stress caused by vertical loads (static), shear stress caused by lateral loads (earthquakes) and propagation of cracks due to successive earthquakes and amortization during centuries [29].

In the load bearing walls of the Naziresha's Mosque serious cracks are present in all façades. Most of the cracks inferred from the damage survey presented a diagonal and vertical trend. Creep of the masonry units is believed to be the cause of vertical parallel cracks which eventually may lead to collapse of the wall. This phenomenon is accompanied by occurrence of chipping and possible local failure. This is very obvious in the north façade where there are massive cracks whose cause is believed to be improper modification of the entrance. Vegetation growth can be seen where masonry units are missing. At the bottom of the walls, due to consequent flooding, sanding phenomenon is seen. There are found voids that grow bigger in time. Crack propagation from pendentives to the load bearing walls is observed in all four facades. In the places where openings are present, a different crack pattern can be seen. Tensile and shear stresses are concentrated close to the edges of these openings possibly due to local concentration of loadings. As a result, every window is cracked at the bottom corners of its frames (Figure 3).

Figure 3 - Cracks in the interior of the dome and pendentives in Mirahor Ilyas Beg Mosque.

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Furthermore, cracks due to differential settlement and suffusion (migration of soil particles through soil skeleton) phenomenon are observed. Hair cracks (small cracks) are seen in the interior of the walls. Further cracks cannot be seen due to local works of rebuilding in the interior of the mosque. However traces of the mentioned cracks of the exterior can be spotted if carefully checked. Based on the problems mentioned above, there is a very concerning situation about structural stability of this mosque.

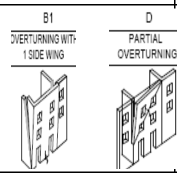
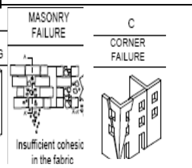
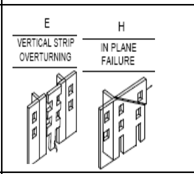
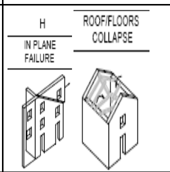
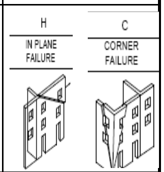
Figure 4 - Propagation of cracks in the load bearing walls, west façade of Naziresha's Mosque

The assessment results are summarized in Table 1.

As expected, stress concentrations were recorded at the corners of openings and wall connection locations. This model output can be easily verified by observing the cracks on the existing structure.

The analysis results mentioned above clearly indicate that the imperfect geometry due to settlement directly affects stress concentration values, which are the key value from which to draw retrofitting strategies for the historical monument. Stress concentration and the period difference from modal analysis between the rough and accurate models provide convincing evidence of the extreme importance of the definition of the correct geometry for this type of structure. Data acquisition with the laser scanner showed that the accurate geometry results in an increase of stress concentrations under seismic load. This limitation changes the possible failure mechanisms and threatens the historic monument if an earthquake were to occur in the area.

Table 1. Structural assessment results

	LEADEN MOSQUE	NAZIRESHA'S MOSQUE	MIRAHOR ILYAS BEG MOSQUE	MURAT BEG MOSQUE	PREZA MOSQUE
DATE	09/09/2011	09/09/2011	09/09/2011	09/09/2011	08/10/2011
ADDRESS & LOCATION / ROUGH AGE OF BUILDING [YEARS]	CITY CENTER OF BERAT, GAQI GJIKA STREET / 40.704497, 19.955453 / YES / 360 yrs	KADRI HYSHMERI STREET, ELBASAN / 41.105294, 20.086495 / YES / 421 yrs	FLORESHA MYTEVELI, KORÇË /40.615940, 20.775407/ YES / 525 yrs	PAZARI I VJETER STREET / 41.509887, 19.794300 / 477 yrs	PREZA CASTLE/41.431 257, 19.672667/ YES/ 464 yrs
STRUCTURAL SYMMETRY	EXISTS IN PLAN	EXISTS IN PLAN	EXISTS IN PLAN	EXISTS IN PLAN	EXISTS IN PLAN
ROUGH AREA COVERED	576 m^2	115 m^2	186 m^2	100 m^2	75 m^2
NO.OF STORIES	1 STORY + mezzanine	1 STORY + mezzanine	1 STORY + mezzanine	1 STORY + mezzanine	1 STORY
TOTAL HEIGHT OF BUILDING [M]	11 m	14.2 m	14.59 m	4.20 m	3.30 m
WALL CONSTRUCTION	BRICK & STONE	BRICK & STONE	BRICK & STONE	BRICK & STONE	BRICK & STONE
WALLS ARE LOAD BEARING	YES	YES	YES	YES	YES
STRUCTURAL QUALITY OF WALLS	ADEQUATE	POOR	ADEQUATE	POOR	POOR
TYPICAL WALL THICKNESS[M]	1.05 m	1 m	1.25 m	0.70 m	0.70 m
LATERAL LOAD RESISTING ELEMENTS	DOME, WALL, PENDENTIVE	DOME, WALL, PENDENTIVE	DOME, WALL, PENDENTIVE	WALL	WALL
CONNECTIONS	ADEQUATE	POOR	GOOD	ADEQUATE	POOR
ROOF	DOME	DOME	DOME	PITCHED ROOF	PITCHED ROOF
MINARETS OR OTHER STRUCTURAL APPENDAGES	YES , external Minaret	YES , external Minaret	YES , external Minaret	YES , external Minaret	NO , minaret destroyed
MORTAR / CEMENTING MATERIAL	OTHER : KHORASAN MORTAR	OTHER : KHORASAN MORTAR	OTHER : KHORASAN MORTAR	OTHER : KHORASAN MORTAR	OTHER : KHORASAN MORTAR
DAMAGE LEVEL : WALLS	MODERATE	SEVERE	MODERATE	MODERATE	SEVERE
DAMAGE LEVEL : ROOF	MODERATE	SEVERE	LIGHT	MODERATE	MODERATE
DAMAGE LEVEL : OTHER ELEMENTS **1. Pendentives** **2. Wall corners** **3. Doors, windows**	1.MODERATE 2.LIGHT 3. LIGHT	MODERATE	1.MODERATE 2.LIGHT 3. LIGHT	MODERATE	MODERATE
POSSIBLE FAILURE MECHANISM					
EARTHQUAKE HAZARD LEVEL	VERY LOW	HIGH	VERY HIGH (highest in Albania)	MODERATE	LOW
RECOMMENDATION	RETROFIT.	FURTHER ANALYSIS & RETROFIT.	RETROFIT.	RETROFIT.	RETROFIT .

5.2. FEM Results

The FEM results of the model with assumed perfect geometry showed that the stresses under dead load are seen to be below the ultimate resistive capacity of materials. The distribution of the compression stresses in the dome is seen to be distributed at the middle part, whereas the tensile stresses are observed in a circumferential direction. The maximum value of principal stress (SMAX) and minimum principal stress (SMIN) are seen at the connection of the main dome with the supporting arches having a maximum value of 0.361 MPa and -0.525 MPa for tensile and compressive stresses, respectively.

In the load bearing walls hoop stress (S11) varies from -0.177 to 0.148 MPa. Comparing the corresponding models under static and earthquake load, the maximum tensile stress that occurs in the structure is 0.361 MPa under static, 0.801 MPa under seismic load and 0.144 s for the first mode. On the other hand, the actual geometric model gives 0.774 MPa under static load, 1.4 MPa under seismic load and 0.174 s for the first mode.

6. BASIS OF INTERVENTION DESIGN

The intervention philosophy aims not only to repair the damaged elements, but also to maintain the ones which may suffer from possible failure in the future and improve structural performance under future earthquake loads. Modified or new structural elements have to assure structural compatibility with the original structure, should not disturb the architectural appearance and aesthetics of the building, must improve the structural performance by respecting the current structural mechanism and should be carefully planned and performed in accordance with international conservation practices and ICOMOS (International Council on Monuments and Sites) Recommendations [30-31].

In the domes, the main concern is to repair the structural cracks and keep them under control, as well as protect the interior from atmospheric agents like rain and snow. In order to achieve this, the roofing system should be improved. The leaden layer of the cap should be checked for possible misalignment of the layers and repaired where damaged. The rainwater runoff system should be improved as it is seen to be inappropriate.

The pitched timber roofs should be repaired after close inspection of the timber beams and the ceiling by substituting damaged elements with new ones. Sagging of the ceiling should be fixed by placing additional load-carrying elements

As seen from the damage survey, the load-bearing walls suffer the most from structural problems. They exhibit both visible surface degradation as well as structural cracks. The proposed intervention procedure consists of reducing the shear and tensile stresses on the walls by adding additional tensile and shear resisting elements where necessary. This would create flexible rather than rigid connections to avoid excess stress concentrations and guarantee the durability of the structure (Anzoni et al., 2009)

6.1. Local reconstruction "cucci scucci"

The areas where sanding phenomenon and loss of masonry units is seen should be repaired using the local "cucci scucci" reconstruction technique. The substituting units must have the same architectural features and should be compatible with original facades. This technique should be used to repair the north and south facades (Figure 4).

Figure 5 - "Cucci scucci" reconstruction technique [24].

6.2. Injection

Non-structural cracks less than 10 mm wide should be filled with hydraulic mortar injection. Mortar should be of Type C (based on natural hydraulic lime) NHL3.5 and well-graded aggregate with a binder: aggregate proportion of $1:2^{1/2}$. Injection mix would seal the cracks, protecting the wall plaster from exposure to water (Figure 6). This process would increase the continuity of masonry and neither aesthetics nor architectural features of the mosques would be altered when applied.

7. CONCLUSION

In this study, structural assessment and strengthening of five historical structures was discussed. Structural deficiencies, variegated crack patterns and other damages were recorded and addressed individually. Visual inspection results showed that one of the five mosques, Naziresha's Mosque particularly, is found to be in a very critical condition. This statement was supported by 3D numerical model and the FEM analysis results. Structural behavior of the undamaged model was investigated under static and dynamic loads and weak locations of potential failure in the structure were identified using SAP2000 software.

Figure 6 - Application of injection mix [24].

Geometric data from TSL were used as input for structural analysis. Based on distress severity retrofitting application were designed. However, the actual figure of the distress could only be observed after removing nonstructural covers from structural element. Therefore design and application of retrofitting needs continues attention.

TSL technology was used to increase accuracy and record definition of the imperfect geometry patterns lying on every side of the structure. The load-bearing capacity of the subsoil is limited, causing large differential settlements towards the south façade, where a railway and motorway are also located.

After the analysis procedure, for the structural elements whose structural performance is not at a satisfactory level, immediate retrofitting and strengthening should be applied in order to avoid further structural degradation.

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