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NUMERICAL INVESTIGATION OF STRENGTHENED VAULTED MASONRY STRUCTURES

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ABSTRACT

Unreinforced masonry arches and vaults are frequent in historic structures worldwide. Many of these structures are subject to deterioration and damage and need strengthening to maintain their stability and preserve the historic value. For design of structural interventions for these structures, analysis is needed to realistically estimate the stresses and deformations after strengthening.The present paper addresses numerical modeling and nonlinear analysis of vaulted masonry vaults structures strengthened by different techniques. The numerical modeling by finite elements and the nonlinear analysis were carried out using commercial software ANSYS 12.0. The proposed model was applied to study the structural behavior of several brick masonry vaults strengthened by traditional techniques such as steel bars, ferro-cement and polymer mortar layers and also using externally bonded fiber-reinforced polymer (FRP) laminates; the analyzed vaults were previously tested in laboratory till failure. For all the studied vaults, the numerical results obtained using the proposed model were in good agreement with those obtained experimentally, which demonstrates the capability of the proposed modeling scheme to simulate efficiently the actual behavior of the strengthened vaults. Comparison of the different strengthening techniques regarding enhancement of the vaults capacity and stiffness showed that FRP overlays gave higher strengthening level where the failure load was double that of the unstrengthened vaults. The proposed modeling approach is thus considered a valid and practical tool for the design of strengthening interventions for contemporary or historic unreinforced masonry structures.

1. INTRODUCTION

Unreinforced masonry arches and vaults are frequent in many ancient and historic structures worldwide. These valuable structures are subject to deterioration and misuse which often necessitate strengthening. Any intervention strategy should be based on a deep understanding of the behavior of the existing structure in addition to its behavior after the proposed retrofit measures are taken [1]. Accurate structural analysis of masonry constructions is a true challenge. Being composed of masonry units bonded by mortar, the mechanical behavior of masonry structural elements exhibits non-homogeneity and directional properties, in addition to cracking due to weakness and brittleness of mortar joints [2]. The usually adopted linear analysis assumes linear isotropic behavior but underestimate the structural capacity of masonry structures in many cases, thus the nonlinear analysis gives better description for the actual behavior and capacity of the structure [3].

In this paper finite element modelling and nonlinear analysis are performed using commercially available computer software ANSYS V.12 [4]. Description of the adopted modelling parameters, material characterization and nonlinear solution parameters is given. Numerical investigation is made for masonry vaults externally strengthened by several techniques such as steel reinforcement bars, ferro-cement and polymer mortar layers in addition to the use of externally bonded laminates of Fibre Reinforced Polymers (FRP), which have been experimentally tested [5, 6]. The obtained numerical results are compared with the published experimental results. Application of the adopted procedure is also made on a historic masonry dome to demonstrate the capability of the proposed analysis to explain its structural behavior before and after strengthening.

2. NUMERICAL MODELLING AND NONLINEAR ANALYSIS

2.1. Approaches for modeling and nonlinear analysis of masonry

To represent the heterogeneous and anisotropic nature of masonry construction by finite elements, different strategies may be followed depending on the level of accuracy and the simplicity desired [3].

(a) *Detailed micro-modeling*: both mortar and masonry units are modeled independently as continuum elements where inelastic properties for each are assigned. Additionally, discontinuous elements are used to model the interface between mortar and units. This kind of analysis needs higher computational effort and is adequate for research or small models for localized analysis.
(b) *Simplified micro-modeling*: expanded units are represented by continuum elements whereas the behavior of the mortar joints and unit-mortar interface is lumped in discontinuous elements, known as interface elements. Masonry is thus considered as a set of elastic blocks bonded by potential fracture/slip lines at the joints. [7]
(c) *Macro-modeling (homogenization theory)*: the masonry units, mortar and mortar-unit interface are smeared out in a homogenous continuum material. Macro models are more applicable when the structure has large dimensions and stresses are uniformly distributed along the macro-length [8].

2.2. Adopted nonlinear material behavior and solution procedure

Within this research work, macro-modeling is adopted where masonry is considered a homogenous continuum for which the macro behavior is simulated through selection of specific material properties [9, 10]. The commercial computer software ANSYS 12.0 [4] is used for finite element discretization and for nonlinear analysis. Multilinear isotropic hardening material is used to simulate the masonry composite (brick and mortar) and the mortar layers. This type of material (MISO) uses the von Mises yield criteria coupled with an isotropic work hardening assumption. The material behavior is described by a multilinear stress-strain curve starting at the origin with positive stress and strain values. The uniaxial behavior is described by a piece-wise linear total stress-total strain curve, starting at the origin, with positive stress and strain values and with initial slope corresponding to the elastic modulus of the material, as shown in Figure 1. Bilinear isotropic hardening material was used to simulate the steel reinforcement and ferro-cement wire mesh as well as the FRP layers, where the von Mises yield criteria coupled with an isotropic work hardening assumption, as shown in Figure 1[4].

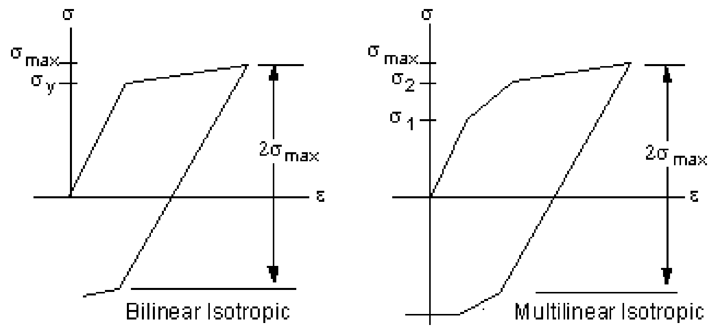


Fig. 1 Multilinear and bilinear stress-strain curves [4].

Structural modeling is made for the masonry using the solid element SOLID65, defined by eight nodes having three translation degrees of freedom at each node, which is capable of cracking in three orthogonal directions, crushing, plastic deformation and creep, and is therefore suitable for nonlinear material properties [9]. The user defines the material tensile strength, compressive strength, and shear transfer coefficient which range from zero for smooth crack (complete loss of shear transfer) to 1.0 representing a rough crack (no loss of shear transfer). When the solution converges to the cracked state, the modulus and consequently the stiffness normal to the crack face is set to zero. The load is applied at increments; within each load step, the computer program may perform several substeps in which equilibrium iterations are made until convergence criteria are satisfied and a converged solution is reached.

3. NUMERICAL STUDY

Numerical modeling and nonlinear analysis were carried out for brick masonry vaults constructed from local bricks and strengthened by different means and previously experimentally tested [5]. The vaults dimensions are shown in Figure 2. Load was placed on the vault top and increased until failure for all vaults to investigate the failure mode and to compare the effectiveness of the strengthening techniques. The obtained numerical results are described and compared to the experimental results. Four strengthening methods for the vaults are illustrated in Figure 3, and may be described as follows:

a. Using 12 steel bars of length 50 cm and diameter 6 mm inserted as near surface reinforcement,
b. Using glass FRP sheet adhered by polyester
c. Using an over layer of sand polyester mortar
d. Using ferro-cement wire mesh 1.5 mm thickness, covered with 1cm mortar layer and shear studs to connect the wire mesh to the masonry vaults.

3.1. Numerical model

A three-dimensional mesh was adopted to simulate vaults; a macro modeling strategy is used. Bricks and mortar joints were discretized using 8-node brick elements SOLID65. Steel rods and ferro-cement wire mesh are discretized using line element LINK8, FRP is modeled using element SHELL63 and the cement mortar and polymer mortar were modeled using SOLID65 [4]. The used model is based upon the crushing and cracking option for SOLID65 element to locate accurately the crack locations. The meshes for unstrengthened and strengthened vaults are shown in Figures 2 and 3, respectively.

3.2. Material properties

The material properties of masonry and the used strengthening materials are as follows [6].

a) Masonry: compressive strength $f'm$ = 4.47 MPa, modulus of elasticity Em = 625 MPa, weight density= 16 kN/m^3, Major Poisson's ratio= 0.15, tensile strength = 0.447 MPa
b) Steel reinforcement: yield stress = 240 MPa
c) FRP: ultimate tensile strength = 3800 MPa, modulus of elasticity = 75000 MPa
d) Ferro-cement mild steel wire mesh: yield stress = 240 MPa

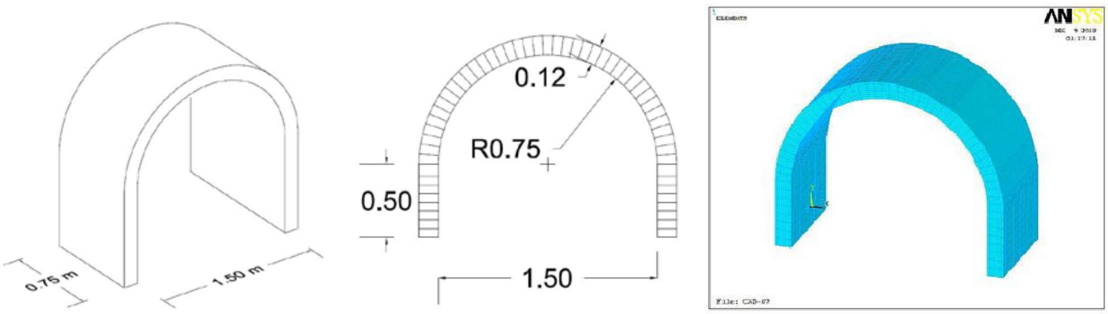


Figure 2: Dimensions and numerical model of the unstrengthened vault.

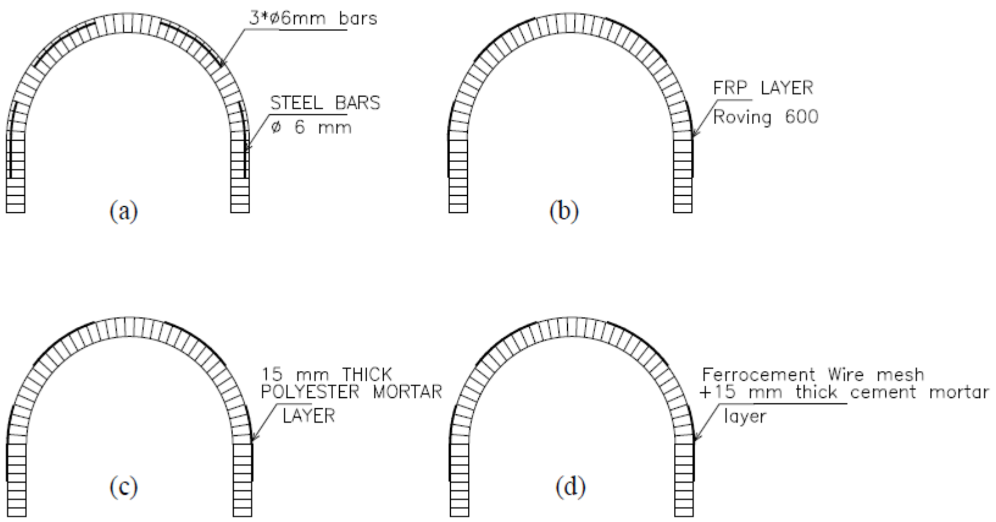


Figure 3: Strengthening techniques for the masonry vaults,
a) Steel reinforcement, b) FRP sheets, c) external polyester mortar layer, d) Ferro-cement wire mesh [5].

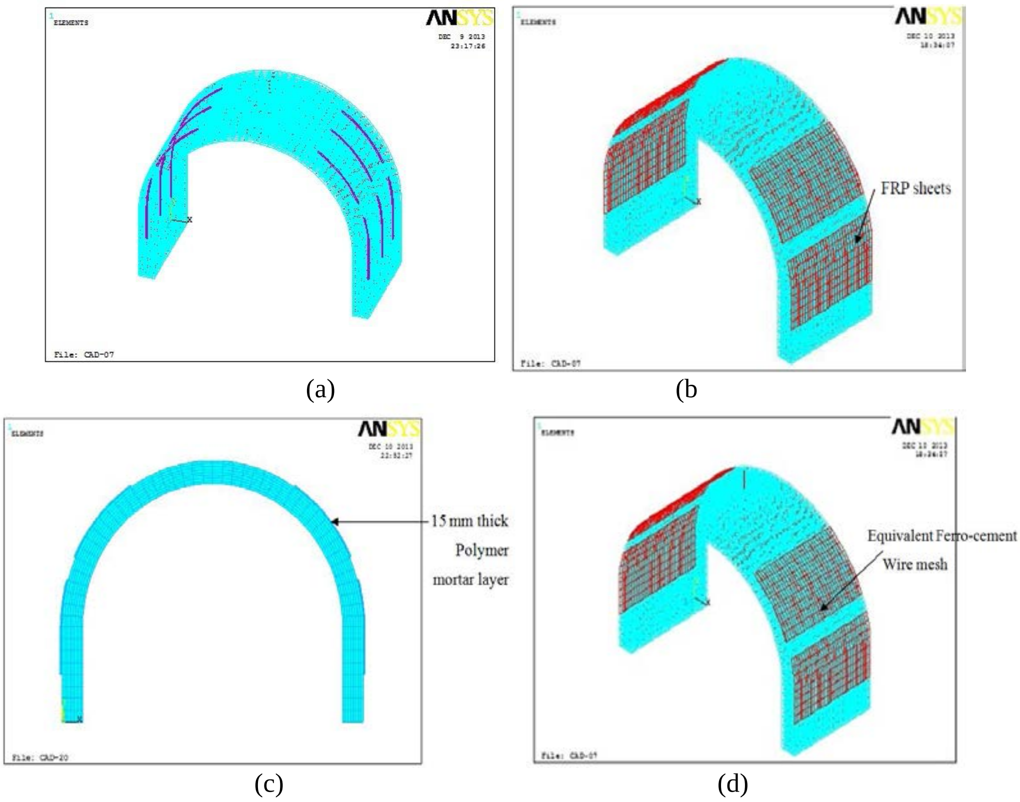


Figure 4: Finite element mesh of the strengthened masonry vaults
a) Steel reinforcement, b) FRP sheets, c) external polyester mortar layer, d) Ferro-cement wire mesh [5].

3.3. Nonlinear analysis parameters

The stress-strain relation for masonry was specified based on properties evaluated experimentally [5]. The coefficients and parameters for nonlinear analysis were assigned the following values [6].

- Shear coefficient along opening cracks (ShrCf-pO) = 0.2
- Shear coefficient along closed cracks (ShCf-Cl) = 0.8
- Tension limit, cracking limit (UnTensSt) = 0.425 MPa

- Compression limit, crushing limit (UnCompSt) = 4.25 MPa
- Number of load substeps solution = 10
- Number of equilibrium iterations = 25
- Convergence criteria: Newton-Raphson (displacement control)

4. NUMERICAL RESULTS AND DISCUSSION

4.1. Failure loads and load-displacement relations

Failure loads predicted numerically for all vaults are given in Table 1, compared to the experimentally determined values (average value). Results show that strengthening with polymer mortar gave slight increase in the ultimate load, rendering this strengthening method the least effective. The other strengthening techniques increased the failure load by about 150% and thus are considered efficient in strengthening masonry vaults. Load-displacement curves for unstrengthened vaults and for vaults strengthened with ferro-cement wire mesh are shown in Figure 5. Acceptable match is observed for the first and last thirds of the curves but the middle third shows deviation from the experimental curves.

Table 1: Failure loads for vaults.

Vault strengthening scheme	Failure load (kN)	
	numerical	experimental (average)
None	8	7.9
Steel reinforcement rods	13.5	12.65
FRP sheets	14	15
Polyester mortar layer	10	9.55
Ferrocement mesh layer	13	12.5

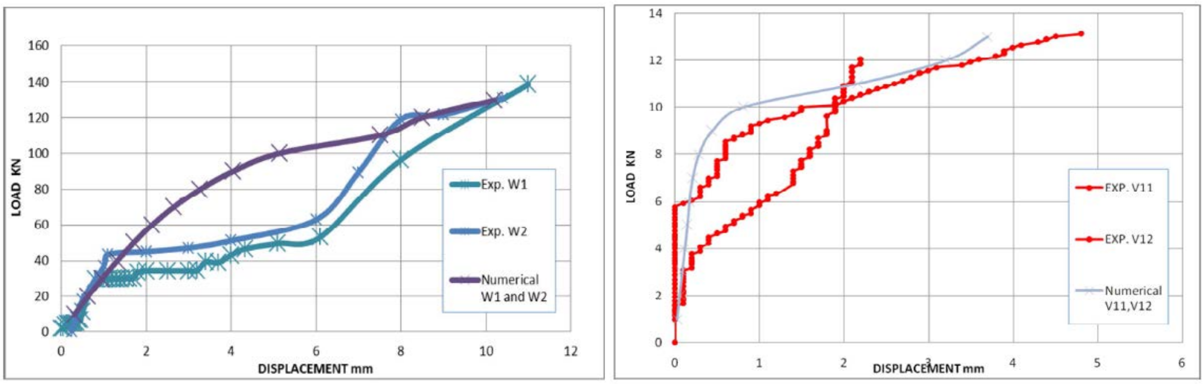


Figure 5: Load displacement curve for unstrengthened vaults and vaults strengthened by ferro-cement wire mesh

4.2. Crack patterns and failure modes

The crack pattern for the unstrengthened vault, shown in Figure 6, indicate failure by formation of three hinges; the same as was observed experimentally. The vaults strengthened using reinforcement steel bars, FRP sheets and ferro-cement wire mesh produced a mode of failure where the crack occurred between the two strengthened zones, as shown in Figures 7 and 8. For the vault strengthened with polymer mortar, the cracks occurred at the same locations as the control vault [5].

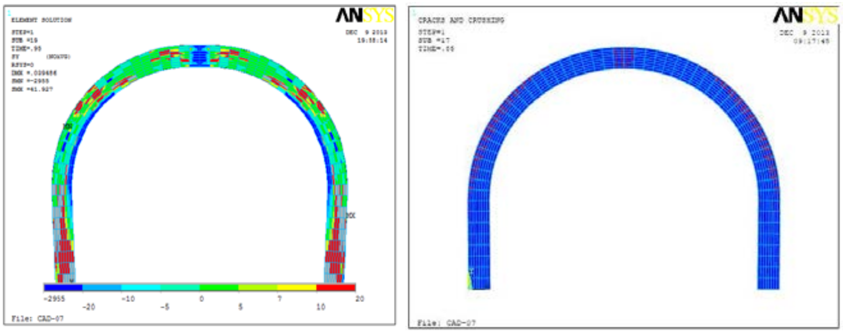
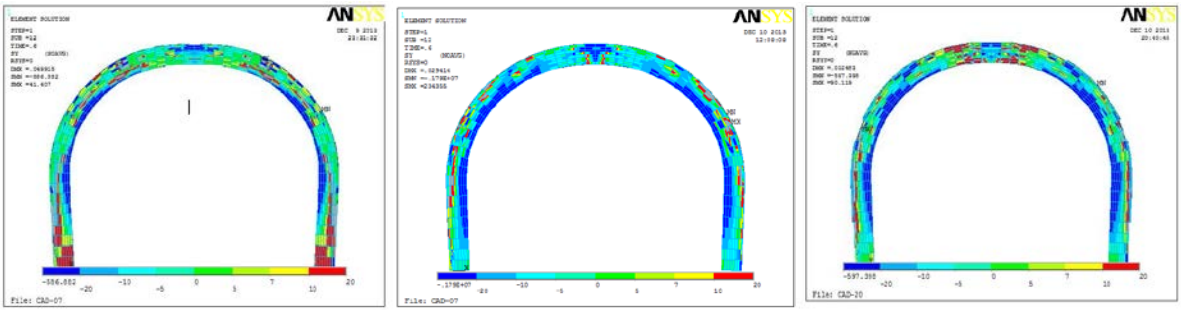
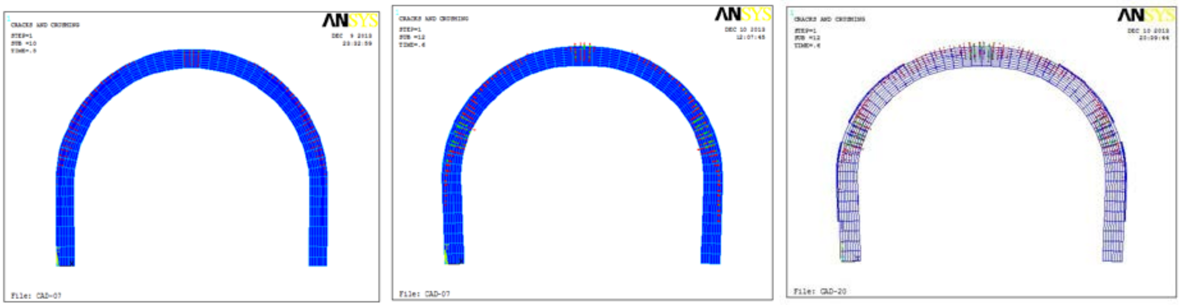


Figure 6: Unstrengthened vault stresses (x10^{-2} MPa) and crack pattern.



(b) (b) (c)

Figure 7: Stresses (x10^{-2} MPa) in the vaults strengthened by
a) Steel reinforcement, b) FRP sheets, c) Ferro-cement wire mesh



(c) (b) (c)

Figure 8: Crack patterns in the vaults strengthened by
a) Steel reinforcement, b) FRP sheets, c) Ferro-cement wire mesh

4.3. Comparison between numerical and experimental results

Numerically predicted ultimate failure loads and displacements at failure were very close to experimental results, which demonstrate the accuracy of the numerical model. The load-displacement curves show acceptable match for the first and last thirds of the curves but the middle third shows differences between numerical and experimental curves. This may be attributed to non-homogeneity of the experimental samples where defects or weak joints may cause stress concentrations.

5. APPLICATION TO ANALYSIS OF A STRENGTHENED HISTORIC DOME

5.1. Description

The dome of Sodoun, built in 1468 in the historic district in Cairo, showed deterioration and noticeable cracks that threatened collapse of the dome. Strengthening was made using carbon fiber reinforced polymer (CFRP) strips bonded to the interior surface of the dome and to the exterior of the supporting drum [11]. The clay brick dome has diameter of 5 m and height 5.5m, and has 18 windows on the perimeter of the drum. It is built over four limestone walls of thickness 0.6 m and height 8m.

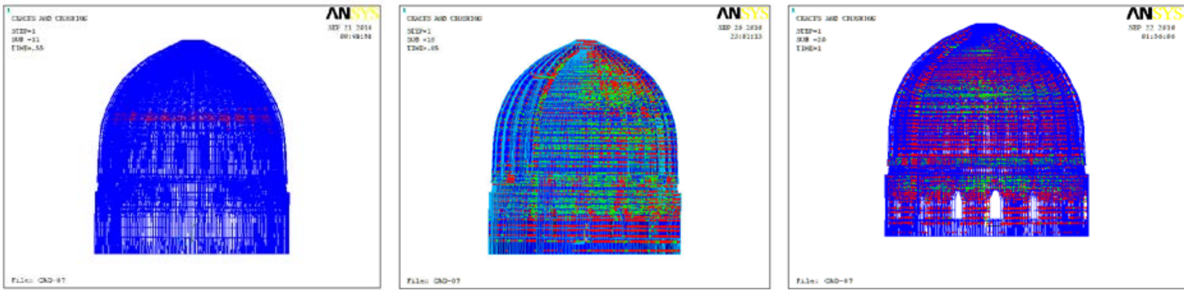
5.2. Numerical modeling and material properties

The numerical study is performed using the adopted finite element modeling. The dome was modeled by SOLID65 elements. The strengthening CFRP sheets and strips were modeled using SHELL63 elements. The material properties for the clay brick masonry of the dome were estimated through field tests and chemical analysis conducted within the restoration project [11]. Values for masonry compressive strength (*f'm*), modulus of elasticity and major Poisson's ratio were 0.85 MPa, 119MPa and 0.15, respectively. These properties were adopted in the present study for the originally built dome and reduced by 20% to represent material deterioration.

In order to study the performance of the dome, three cases were modeled and analyzed: the original non-cracked dome having the estimated masonry material properties, the deteriorated dome with reduced material properties, and the deteriorated cracked dome strengthened by the applied CFRP strengthening scheme. The own weight and imposed loads were applied in 20 load steps [6].

5.3. Numerical results and discussion

For the deteriorated dome, the numerical results showed first cracking at load step 11, Figure 9(a), very similar to the reported observed cracks [11]. By increasing the load, the last load step gave non-converged solution, indicating that material deterioration can cause total failure. The crack pattern for before failure is shown in Figure 9(b). Analysis of the deteriorated strengthened dome shows that the CFRP strengthening system managed to prevent propagation of the first crack. By increasing the load, the final crack pattern at load step 20, shown in Figure 9(c), where a converged solution was reached. In spite of the crack pattern, the dome was still stable and total failure did not occur. This also proves the efficiency of the used strengthening system to avoid the dome failure and total collapse.



(a) (b) (c)

Figure 10: Crack patterns for a) deteriorated unstrengthened dome at first cracks, b) deteriorated unstrengthened dome before failure, c) FRP strengthened dome before failure

6. CONCLUSIONS AND RECOMMENDATIONS

This paper presented nonlinear analysis of unreinforced masonry vaulted elements externally strengthened by different techniques. The main conclusions drawn can be given as follows.

- Numerical modeling and nonlinear analysis were done using a commercially available computer program (ANSYS), which renders the approach applicable by a practicing engineer.
- Numerical results showed good agreement with published experimental results regarding ultimate load and crack pattern. Numerical prediction for the load displacement curve showed acceptable match except for the middle third of the curve.
- Strengthening of masonry vaults using steel reinforcement, FRP externally bonded sheets and ferro-cement wire mesh increased the ultimate loads to 150 %, 190% and 150% of the unstrengthened vaults, respectively, while strengthening with polymer mortar layer had slight strengthening effect.

- External FRP strengthening nearly doubled the ultimate capacity and improved the failure mode. Other advantages such as ease of installation, small thickness, minimum intervention and reversibility make FRP an attractive alternative for traditional strengthening methods.
- Application on a historic dome demonstrated the capability of the adopted procedure to simulate the structural behavior of heritage masonry structures. The model can be efficiently used to justify cracking and predict the failure loads of such structures. It can also be used to propose and design appropriate strengthening schemes for retrofit, thus preserving and enhancing the safety of distressed or damaged heritage structures.
- The adopted numerical modelling may thus be regarded as a reliable tool to explore and compare the effectiveness of different proposed strengthening schemes and predict the failure mode, ultimate load-carrying capacity and safety level of such structures.
- The research could be extended to allow for use of other strengthening techniques such as prestressed FRP laminates, post-tensioning steel or FRP rods, and other.
- It is recommended to conduct more extensive numerical studies using more sophisticated material models in order to represent debonding and delamination.
- Further research is suggested to study the nonlinear behavior of masonry structures subject to dynamic loads such as impact, cyclic loading, vibrations or earthquakes.

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