PACE-2021
International Congress on the
Phenomenological Aspects of Civil Engineering
Research Article 20-23 June 2021

Numerical Investigation of the Effective Strengthening Arrangements by Using CFRP for Historical Masonry Vaults

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Keywords

Masonry vault,
CFRP Fabric,
Strengthening,
Ansys,
Numerical Analysis

Abstract

Vaults are the most important structural elements in historical masonry structures. The issue of strengthening these structural elements continues to be popular and important in order to best fulfil the task of transferring historical structures to future generations. The use of fibre-reinforced polymer materials, which emerged in parallel with the developing technology, in reinforcement applications is a common practice. In addition to the many advantages these materials provide, their high cost has led many researchers to determine the most appropriate reinforcement arrangement. Therefore, many studies in the relevant literature are devoted to experimentally and numerically determine the most appropriate reinforcement arrangements of masonry structural members. Within the scope of this study, a vault in the historical Aziziye redoubt was modelled numerically and the effectiveness of two different reinforcement arrangements with CFRP fabric materials as longitudinal and curvilinear was investigated. According to the results obtained, it has been revealed in which situations these regulations are superior to each other.

1. Introduction

Although it has been subjected to various loads for years, the restoration and strengthening of historical buildings that have survived until today is an important issue in terms of the transfer of historical heritage to future generations. In repairing and strengthening historical masonry structures; Cement Injection, Reinforced Concrete jacketing, Strengthening with Reinforced Concrete Beams, Strengthening with Steel Profiles, Strengthening with Torsion Bars are traditionally used methods. The methods used for this purpose bring along disadvantages (Cancelliere et al. 2010; Szolomicki et al. 2015). The idea of using new technological materials in strengthening applications has arisen due to the disadvantages of traditional materials such as having low strength, increasing dead load, changing the structure system and appearance, and the inability of steel and reinforced concrete elements to work effectively with existing stone and brick elements. In recent years, it has been proven by various studies that new materials produced in parallel with the advancement of technology can help overcome these disadvantaged situations. These materials used in strengthening applications are composite materials which are produced in the form of fabric by using single and multifarious fibers and in various applications and have become frequently used in practice. These materials, which are called fiber reinforced polymer materials, are produced from fibers with good mechanical properties such as carbon, aramid, glass, and basalt (Valuzzi et al. 2001; Szolomicki et al. 2015; Oliveira et al. 2010). However, materials produced with carbon fiber having better mechanical properties than other fibers find more applications and offer more active strengthening. Due to its superior mechanical properties, this material is considered to be of high benefit when used for strengthening purposes.

There are many studies in the literature (Valluzzi et al. 2001; Cancelliere et al. 2010; Oliveira et al. 2010; Borri et al. 2011; Rovero et al. 2012; Cakir and Uysal, 2015; Corradi et al. 2015; Szołomicki et al. 2015; Gattesco and Boem, 2019) on the strengthening of arches and vaults with FRP composites, which are critical elements of masonry structures. Although these studies are generally focused on identifying the best strengthening arrangements, the information on this subject is still limited and there is a need for a large number of strengthening arrangements. In this study, various strengthening arrangements are proposed for the use of CFRP fabric composites in the strengthening of vaults. In addition, due to the difficulties in the modeling of masonry structures and composite materials, the deficiencies of static and dynamic analysis of strengthened masonry structures by composite materials can be seen in the literature.

In this study in order to perform numerical analysis of masonry structures based on the use of the finite element method, from the proposed approaches macro-modeling approach is adopted. It has been focused on strengthening the vaults, which are the critical elements of historical buildings, which were built to build large spannings in historical buildings and which could lead to a devastating effect when exposed to damage.

This study aims at the following;

-to eliminate these shortcomings in the literature,

-to determine the most effective strengthening arrangement by comparing various strengthening arrangements,

2. Material and Method

2.1. Mechanical Characterizations of Materials

Samples of brick vaults in the Aziziye redoubts in Erzurum province were examined and measurements were taken on a determined brick vault and modeled in Solidworks program. As a result of the investigations carried out in Aziziye redoubts, it was seen that as masonry unit the Harman brick and the horasan mortar had been used. In order to perform the analysis by using the macro modeling method, the mechanical properties of the Harman brick and the horasan mortar were taken from the data in the literature and were presented in Table 1. By means of a homogenization formula, the mechanical properties of the masonry were determined. These properties were defined in the created unstrengthened vault model and analyzed by the Ansys Workbench program. In the results obtained from analyses, the tensile stresses were investigated.

Table 1. Material Properties (Binici et al 2014; Cakir 2014)

Material	Harman Brick	Horasan Mortar
Young Modulus(Mpa)	2232	3200
Unit Volume Weight (kg/m3)	1650	1500
Poisson Ratio	0,2	0,2

The elastic modulus of the new composite material was calculated by using the values presented in the table using (1) formula proposed by Lourenço et al. (2002) This new elasticity module was defined to the models in the analyzes made using the macro modelling method in which the structure was defined as a single material.

$$E_a = \frac{t_m + t_u}{\frac{t_m}{E_m} + \frac{t_u}{E_u}} \tag{1}$$

Here;

t_m: the thickness of the mortar,

t_u: the thickness of the masonry element,

E_m: Young modulus of the mortar,

E_u: Young modulus of the masonry element,

Ea: represents the Young modulus of the new composite material.

Obtained from the drawings as t_m = 88.38 mm and t_u = 120 mm. E_m = 3200 MPa and E_u = 2232 MPa are taken as given in the Table 1.

According to (1) formula, the modulus of elasticity was calculated as 2560,511 MPa. The properties of the CFRP fabric material with a thickness of 0.125 mm were taken from the manufacturer's database. The Young modulus is 135000 MPa and the Poisson ratio is 0.3.

2.1. Geometrical Properties and Boundary Conditions

The barrel vault model with a thickness of 260 mm, an spanning of 1000 mm and a depth of 2500 is presented in Fig 1. Fig 1 also shows the used mesh situation. In two different categories called longitudinal and curvilinear, strengthening arrangements have been determined and presented for both categories (Fig 2.), both internally and externally. The amount of CFRP fabric material used in the arrangements is almost equal in volume and thus comparable.

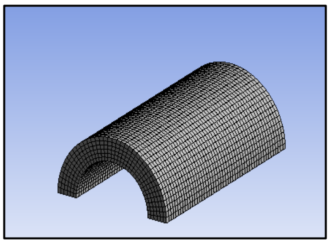
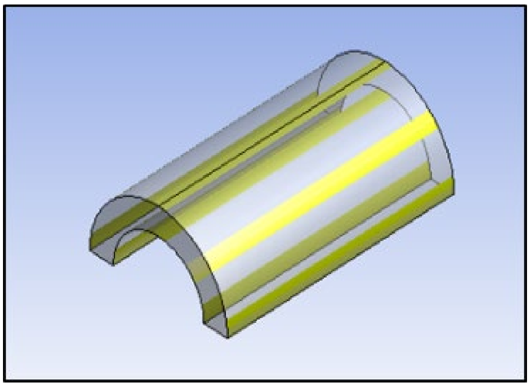


Figure 1. Vault model and mesh situation

The model was fixed to the floor by both feet. A line load of 40 N/mm was applied across the depth from the top of the vault.



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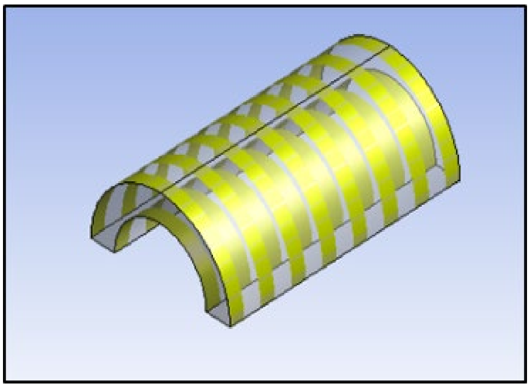


(b)

Figure 2. Strengthening arrangements (a) longitudinal (b) curvilinear

2.2. Numerical Analyses

Numerical analysis of masonry structures is a complex problem due to the heterogeneous nature of the masonry. However, thanks to the developments in computer technology in recent years, many methods have been proposed on the analysis of masonry structures. Micro-modeling, simplified micro modeling and macro modeling methods are generally used for the analysis of masonry structures(Fig. 3). The micro modelling method is considered the complex structure of the method, the large number of finite elements in the case of the large size of the structure and the fact that the number of elements in the case of strengthening will increase further. For these reasons, it will easily understandable that the method requires considerable time and effort. In most cases, computer capabilities as well do not allow micro-modeling. In the literature, macro modeling method which is suggested as an approach which can give enough accuracy in these cases is frequently used. Macro modeling method is based on obtaining the mechanical properties of the composite material by combining mechanical properties of the masonry units in homogenization formulas by considering mechanical properties as a single composite material. In this way, the masonry structure consisting of a large number of units is considered to be composed of a single unit as a whole and the number of elements is significantly reduced.

Assuming a perfect bond between the masonry and the CFRP fabric. In addition, linear elastic isotropic material behavior is assumed for materials and macro modelling method is adopted.

SOLIDWORKS and ANSYS programs were used for modelling and analyzing, respectively.

The SOLID186 element type is used to divide the masonry structure into finite elements, which is generally preferred in the literature. SOLID186 is a 3-dimensional high-level solid element with 20 nodes.

The element is made up of 20 points, each with three degrees of freedom.

SHELL181 elements form the finite element meshing of strengthening materials. The SHELL181 element type is appropriate for the analysis of layered structures ranging in thickness from thin to medium. For layered applications, it can be used to model composite layers.

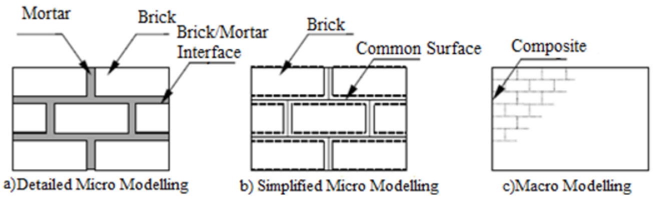
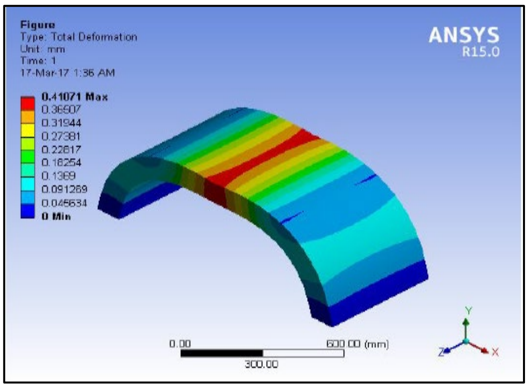


Figure 3. Modelling techniques used in masonry structures

2.3. Verification of the Numerical Method Used

The study by Nissar(2017) was used to validate the method adopted in the current study. In the study by Nissar(2017), 100 mm thickness arches with 1000 mm diameter, 400 mm height and 500 mm depth were investigated both experimentally and numerically. The applied load and response along the peak line were recorded, and then the experimental study was verified with the macro modeling method in the Ansys Workbench program. A linear loading of 20 N/mm obtained experimentally was used in the analyses. The linear elastic isotropic assumption was adopted. The material properties used in modeling are presented in Table 2. The results of the reference article and the results obtained in the current study are presented in the Figure 4. As it can be clearly seen from the Figure 4, the results of the current study are quite consistent with the reference article.



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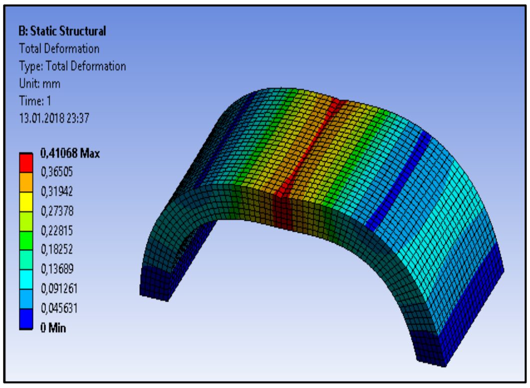


(b)

Figure 4. (a) Static analysis total deformation result (Zaid Bin Nissar 2017) (b) Static analysis result obtained in the current study

Table 2. Material Properties (Nissar 2017)

Material	Brick	Mortar	New Composite Material
Young Modulus(Mpa)	2289	3750	1183

After it was understood that the numerical model used would be a good representation for the stacking behavior, the numerical analysis of the models, which is the subject of the current study, was carried out.

3. Results and Discussions

The strengthening applications were analyzed on the determined strengthening types. The mechanical properties of CFRP materials used as strengthening materials are taken from the manufacturer database. Solid elements were used for the vault and Shell elements were used for the strengthening materials. Static analysis was performed on the models. According to static analysis; total deformation and tensile stress values due to static line load were determined.

Firstly, the tensile stress distribution for the reference accepted unreinforced vault model is presented in the Figure 5. Accordingly, the maximum tensile stress occurs throughout the depth in the middle intrados of the vault. Maximum principal stress value is 0.3396 MPa. In addition, it is clearly seen that the maximum tensile stress distribution is compatible with the vault fracture mechanism. The greatest tensile stresses occurred in the middle intrados of the vault and the back parts. it was determined that total deformation was limited in both strengthening arrangements. In addition, it was determined that CFRP could provide considerable tensile stress limitation. Figure 7 and Figure 9 show stress distrubition of CFRP materials. These distributions also confirm the fracture mechanism of vault.

Considering the stress distribution of the reinforced vault, it is seen that the strengthening materials significantly limit the stresses in the middle intrados where the maximum stress occurs, and by carrying the stresses in the back part, the stress distribution in the back part resembles the regions with less tensile stress(Fig.6. and Fig.8.).

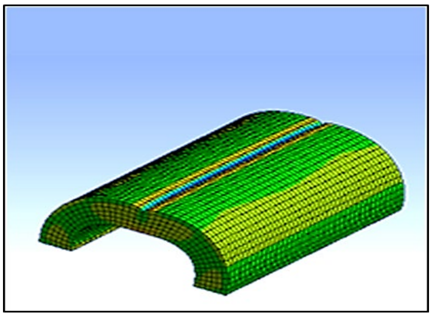
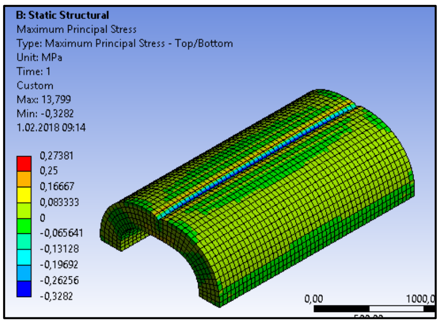


Figure 5. Maximum principal stress distribution for unstrengthened vault



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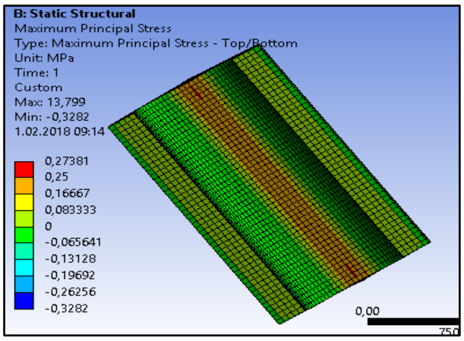
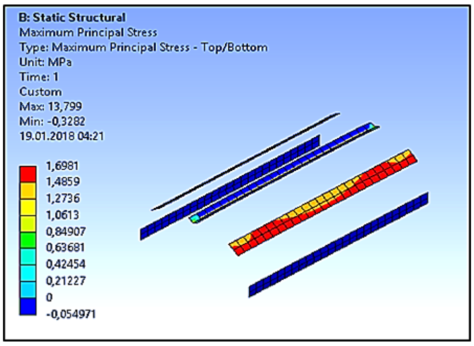


(b)

Figure 6. Maximum principal stress distribution for longitudinal strengthened vault (a) top view (b) bottom view



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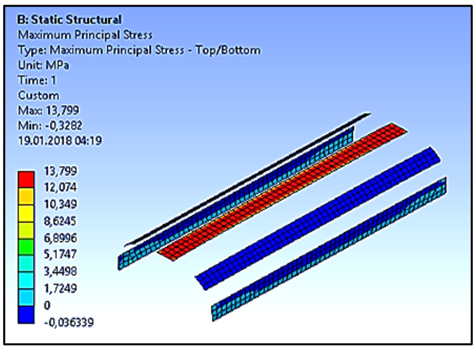
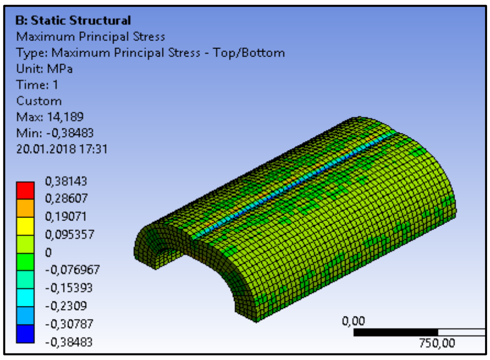


(b)

Figure 7. Maximum principal stress distribution CFRP materials for longitudinal strengthening situation



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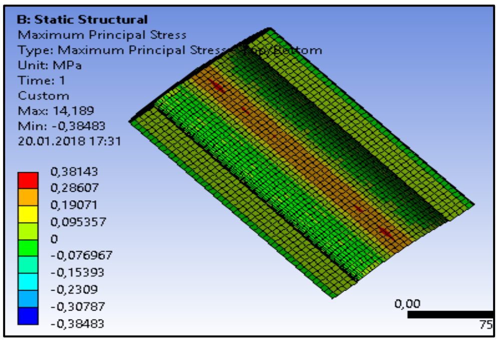
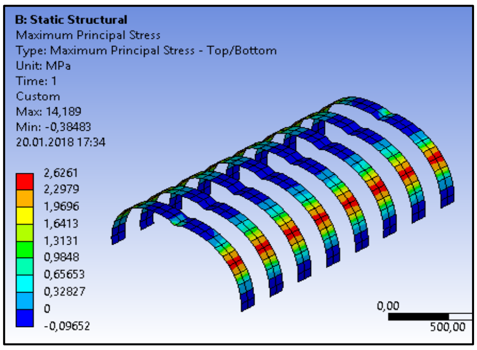


(b)

Figure 8. Maximum principal stress distribution for curvilinear strengthened vault (a) top view(b)bottom view



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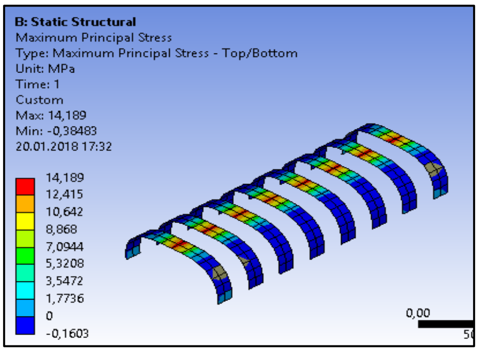

(b)

Figure 9. Maximum principal stress distribution for curvilinear strengthening situation

In more detail, the maximum tensile stress to which the vault is subjected in the unreinforced condition is 0.3396 MPa, while it is 0.25 MPa in the case of longitudinal strengthening and 0.29 MPa in the case of curvilinear strengthening. In other words, while longitudinal reinforcement reduces the maximum tensile stress of the unreinforced vault by 51%, this rate is 44% in curvilinear reinforcement. On the other hand, although longitudinal reinforcement can limit the displacement of the unreinforced vault by 5%, the displacement limitation rate in curvilinear reinforcement is 10%. In this case, it is recommended to apply longitudinal reinforcement when tensile stresses need to be limited, and curvilinear reinforcement to apply when displacements need to be limited.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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