





Research Article

Strengthening of historic masonry vaults with CFRP prepreg

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ABSTRACT

Masonry vaults, frequently used in historic buildings to create large openings, have played a critical role in the survival of these buildings to the present day. These structural elements, which have been exposed to destructive effects such as earthquakes for centuries, need strengthening activities in order to transfer cultural heritage to future generations. The use of composite materials with high mechanical properties for strengthening purposes has been a popular method since the beginning of the 21st century, and its effectiveness has been proven. In this study, a masonry vault in the historical redoubts located in Erzurum, Türkiye, was modelled, and the effectiveness of various strengthening scenarios using prepreg composites was investigated. Numerical simulations were conducted with the Finite element method-based macro modelling approach. The investigation revealed that retrofitting arrangements maintained the stress distribution in masonry vaults while reducing maximum tensile stress; intrados reinforcement proved more effective, particularly the intrados-straight retrofit, with a 24% improvement, whereas extrados strengthening showed limited effectiveness.

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1. Introduction

Anatolia has been home to many civilisations from the past to the present. It is, therefore, rich in architectural works that are an important part of the cultures of these civilisations. These historical buildings, mostly constructed in the masonry building system consisting of mortar and assembled units, have been exposed to destructive effects such as earthquakes since their existence. Repair and strengthening works are vital for transferring this cultural heritage to the future. The fact that traditional strengthening methods have many disadvantages has necessitated the search for alternative methods. In parallel with technology development, using composites called fibre-reinforced polymers, obtained by combining fibres with high-strength properties with the help of epoxy resin, has become widespread in the last twenty years. In particular, composites produced by applying a pre-resin impregnation process called prepreg stand out as advanced composites. The adaptability of fibre-reinforced composites to curved geometries due to their thin and flexible nature makes it possible to use them to reinforce masonry curved structural elements.

Studies on using prepreg composites to strengthen masonry structures are limited (Cakir and Uysal 2015). Although composite materials are a proven method for retrofitting (Mahini et al. 2012; Alecci et al. 2017; Zhang et al. 2017; Hamdy et al. 2018; Tarhan and Uysal 2023), there are still critical engineering and economic issues such as application location and the amount of material to be used.

This study aims to numerically investigate the effectiveness of prepreg composites in strengthening historic masonry vaults and contributing to preserving and transferring historical structures for future generations.

2. Material and Method

2.1. Geometrical and mechanical properties of the masonry vault

To obtain the material parameter to be used in numerical simulations, the material properties of the components that make up the masonry are needed. A

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masonry vault in the historical redoubts located in Aziziye, Erzurum, was monitored, and it was seen that the masonry components used in the masonry vault were Harman brick and Khorasan mortar. The material properties of the Harman brick and Khorasan mortar were taken from the literature and presented in Table 1.

The semicircular masonry barrel vault, the subject of the numerical investigation and whose sectional views are presented in Fig. 1, has a span of 100 cm, a thickness of 26 cm and a depth of 250 cm. Characteristics of the 0.125 mm thick CFRP prepreg material were taken from the manufacturer's database. The Poisson's ratio is 0.3, and Young's modulus is 1.35×10^5 MPa.

Table 1. Material properties from literature (Binici et al. 2014; Çakır and Uysal 2015).

| Materials | Young's modulus (N/mm ²) | Unit volume weight (kg/m ³) | Poisson's ratio |
|-----------------|--------------------------------------|---|-----------------|
| Harman brick | 2232 | 1650 | 0.2 |
| Khorasan mortar | 3200 | 1500 | 0.2 |

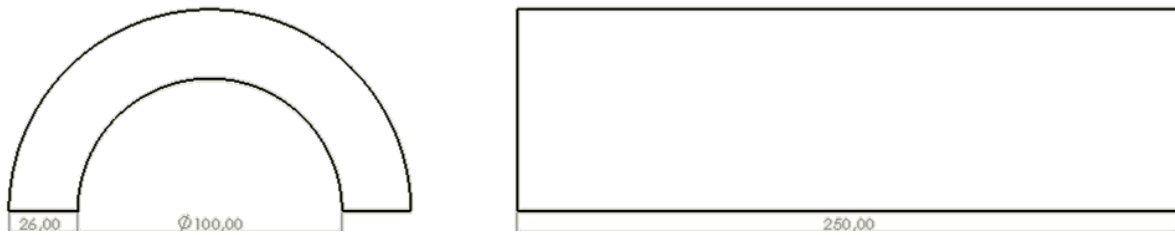


Fig. 1. Geometrical properties of the masonry vault.

2.2. Numerical modelling

The numerical modelling of masonry is a complex problem due to the heterogeneous nature of masonry. The modelling methods are based on three approaches (Fig. 2). These approaches are micro modelling, simplified micro modelling and macro modelling. Although more accurate and detailed solutions can be obtained with the micro-modelling approach in which masonry units and mortar are modelled separately, it is preferred for solving small-sized problems due to the computa-

tional burden required. On the other hand, the macro modelling approach, which considers masonry as a single composite material, provides fast and highly accurate results about the global behaviour of the structure or structural element. Macro modelling is a popular method due to the low computational load and result file storage requirements (Lourenço et al. 1996).

In this study, the macro modelling method was adopted, assuming that the masonry shows isotropic and linear elastic behaviour as Tarhan and Uysal (2023) followed.

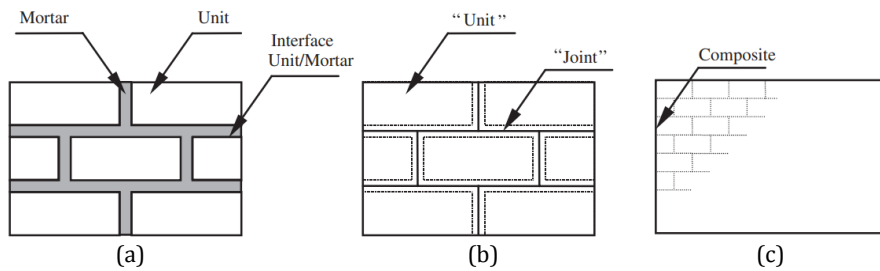


Fig. 2. Modelling methods for masonry structures:
(a) Detailed micro-modelling; (b) Simplified micro-modelling; (c) Macro-modelling.

The Young's modulus of the homogeneous material consisting of a combination of unit and mortar was calculated using Eq. (1) proposed by Lourenço et al. (2002).

$$E_a = \frac{t_m + t_b}{\frac{t_m}{E_m} + \frac{t_b}{E_b}} \quad (1)$$

where t_m , t_b , E_m and E_b represent the thickness and Young's modulus for mortar and brick, respectively, and E_a represents Young's modulus of the new composite material. According to the formulation, Young's modulus

of the new material was calculated as 2560.5 MPa and defined in the numerical model. The material properties adopted for the numerical model are presented in Table 2. Details can be found in Tarhan (2018).

Solidworks and ANSYS Workbench programs were used to create and analyse the models. The numerical model was divided into finite elements with a size of approximately 50 mm (Fig. 3). The numerical model, fixed to the ground at both feet, was statically analysed under gravity. A 40 N/mm load was applied from the middle of the spanning through its depth in addition to gravity load.

Table 2. Material parameters used in modelling.

| Materials | Young's modulus (N/mm ²) | Unit volume weight (kg/m ³) | Poisson's ratio |
|--------------|--------------------------------------|---|-----------------|
| Masonry | 2560.5 | 1543.7 | 0.2 |
| CFRP Prepreg | 135000 | 1600 | 0.3 |

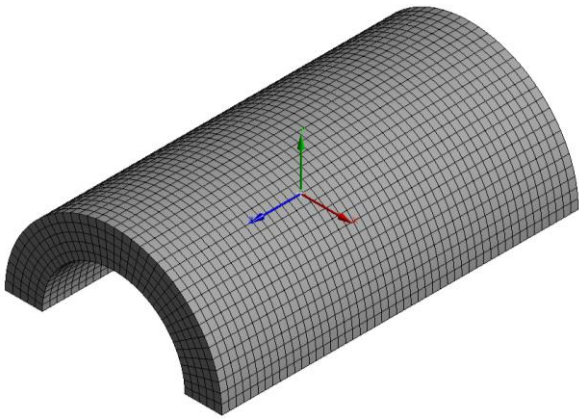


Fig. 3. View of the model divided into finite elements in 50 mm size.

Four different composite layouts were determined as reinforcement arrangements considering the inner and outer surfaces of the vault separately. For the reinforcement arrangements, 15 cm wide strips were used. Depending on the path followed by the composite, these arrangements were considered in two categories: straight and curved. The straight composite arrangement represents the case where the placement of CFRP prepreg material follows a straight line along the vault depth. The

curved category refers to the composite placement along the curved path of the vault. In the straight reinforcement arrangement, the composites were applied in five pieces from the intrados of the vault and along a depth of 2.5 m. The composite strips were applied at 20 cm intervals in the case of intrados reinforcement, while the intervals were 40 cm in the case of extrados strengthening. In the curved reinforcement arrangement, eight pieces of composite strips were placed at 18.5 cm intervals along the depth of the vault. The volume of material used in all arrangements is approximately equal. For more information, see Tarhan (2018). The view of the reinforcement type is given in Fig. 4.

In order to clarify the comparison of retrofitting arrangements and the conclusions, a simple formulation named the percentage of effectiveness (*PE*) was used, presented in Eq. (2), where the change in maximum tensile stress is expressed as a percentage.

$$PE = \frac{|\sigma_i - \sigma_{ii}|}{\sigma_i} \times 100 \tag{2}$$

Here, σ_i represents the maximum tensile stress in the reference, i.e., the unreinforced vault model, and σ_{ii} represents the maximum tensile stress in the model reinforced with the retrofitting arrangement for which the effectiveness percentage is calculated.

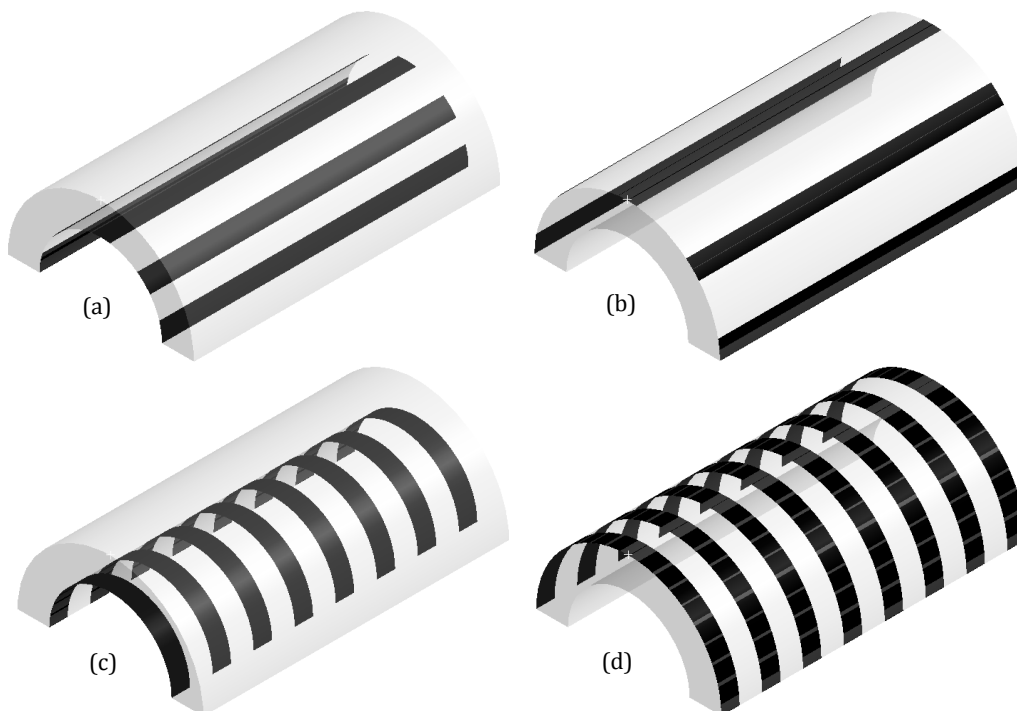


Fig. 4. Reinforcement arrangements: a) Intrados-straight layout; b) Extrados-straight layout; c) Intrados-curved layout; d) Extrados-curved layout.

Table 3. The number of elements and nodes depending on the strengthening type.

| Strengthening arrangement | Number of elements | Number of nodes |
|----------------------------|--------------------|-----------------|
| Unstrengthened (Reference) | 9000 | 42873 |
| Intrados - straight | 10250 | 46227 |
| Extrados - straight | 10250 | 46227 |
| Intrados - curved | 10662 | 47622 |
| Extrados - curved | 10662 | 47622 |

3. Results and Discussion

In this section, the numerical analysis results of the proposed retrofitting arrangements are evaluated regarding maximum principal stress, referencing the results of the unreinforced masonry vault model.

Unreinforced masonry vault analysis results are presented in Fig. 5. The distribution of tensile stresses occurred parallel to the classical five hinge formation re-

gion in the intrados part of the vault crown region, the vault back, and the support region intrados of the vault. It was determined that the maximum tensile stress of 0.34 MPa occurred in the vault crown region and the intrados part. In the stress distribution, some tensile stress accumulation was observed adjacent to the applied line loading. Since this distribution is due to the type of load application, it is not a location where tensile stress is expected to occur and was ignored in the evaluation.

The tensile stress distribution of the masonry vault reinforced with the intrados-straight reinforcement arrangement is presented in Fig. 6. The distribution of tensile stress did not change in general, and the maximum tensile stress value was found to be 0.26 MPa. PE was determined as 24%.

The results of the analysis of the reinforced model with the arrangement in which the composite layout is applied from extrados and straight are presented in Fig. 7. Maximum principal stress distribution has the same distribution as the reference. The maximum tensile stress value is 0.33 MPa and has the same distribution. The PE of this strengthening arrangement is 3%.

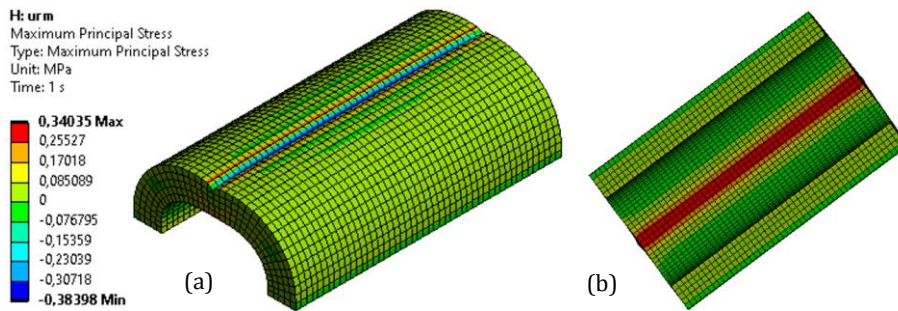


Fig. 5. Maximum principal stress distribution of unreinforced model: a) Isometric view; b) Bottom view.

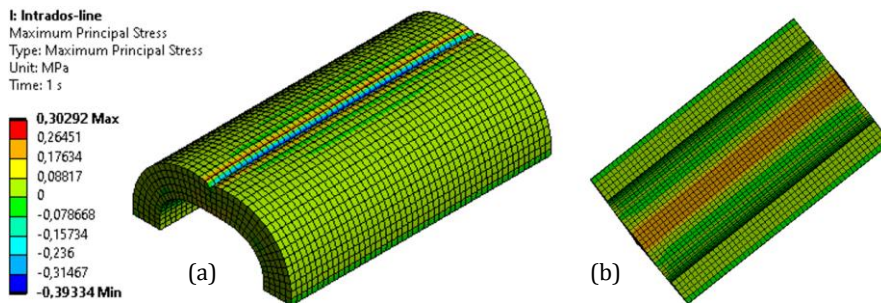


Fig. 6. Maximum principal stress distribution (intrados-straight reinforcement): a) Isometric view; b) Bottom view.

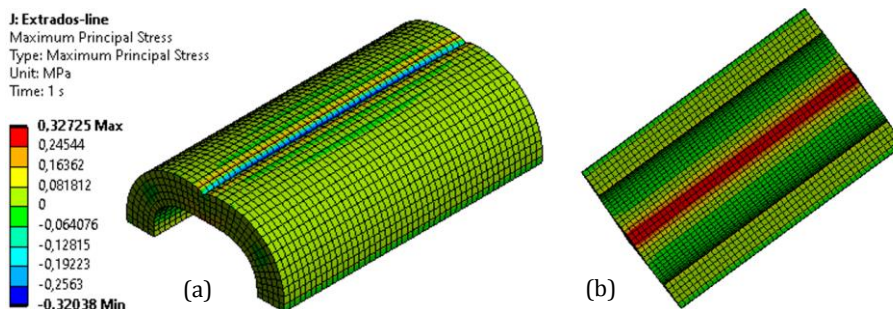


Fig. 7. Maximum principal stress distribution (extrados-straight reinforcement): a) Isometric view; b) Bottom view.

The maximum tensile stress was determined as 0.31 MPa in the intrados-curved arrangement with 9% PE, whose stress distribution is presented in Fig. 8. In addition, the stress distribution varies in a wide range in the region where the maximum tensile stress occurs. Accordingly, as shown in Fig. 8, the stress distribution in the area where the maximum stress occurs is not uniform, unlike the others.

The stress distribution of the reinforced model with the composite arrangement on the extrados and along the curved path is presented in Fig. 9. The maximum tensile stress value was almost the same as the reference value, and a PE of 0.8% was obtained.

The maximum tensile stress values of the models and

the effectiveness percentages obtained from the models are presented in Fig. 10, together with the reinforcement category and location information. As stated by Valluzzi et al. (2001) and Foraboschi (2004), all of the models reinforced with composite increased the load-carrying capacity. Foraboschi (2004), Oliveira et al. (2010) and Tarhan and Uysal (2023) reported that intrados strengthening is more effective, as found in this study. The most effective reinforcement arrangement was identified as intrados-straight. Moreover, straight reinforcement was more effective than the curved one of the arrangements with the same location. On the other hand, the extrados strengthening arrangement was insufficient to limit the tensile stresses in the reference model.

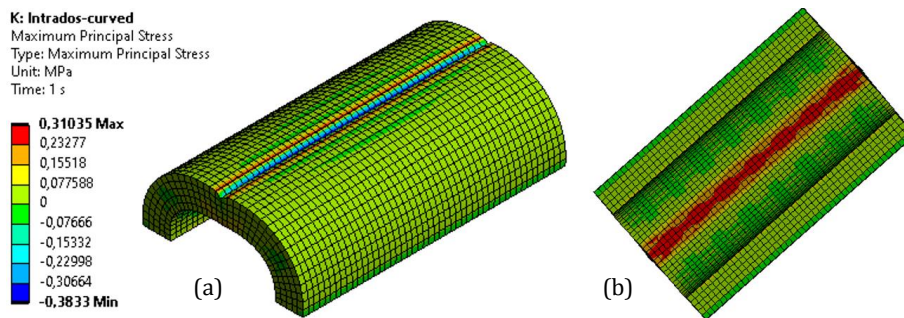


Fig. 8. Maximum principal stress distribution (intrados-curved reinforcement): a) Isometric view; b) Bottom view.

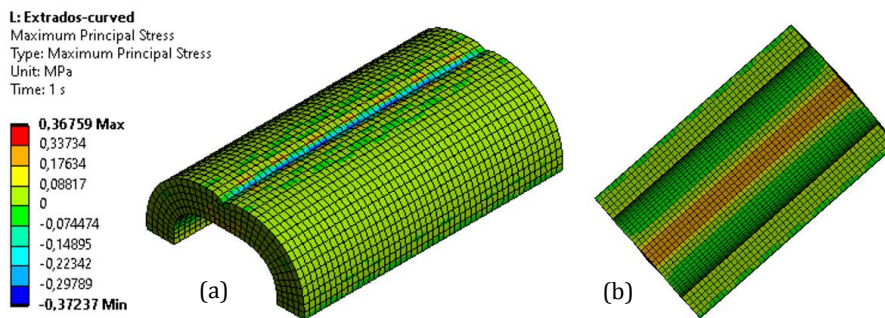


Fig. 9. Maximum principal stress distribution (extrados-curved reinforcement): a) Isometric view; b) Bottom view.

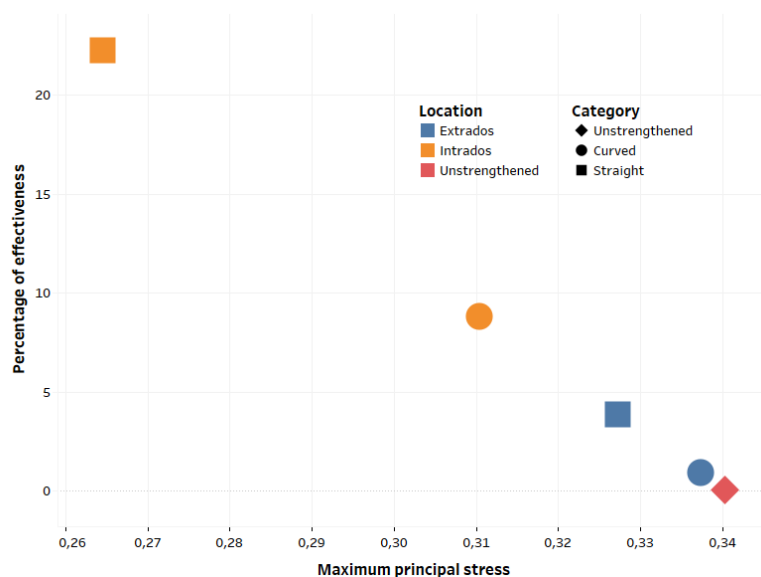


Fig. 10. Effectiveness of models regarding restricting maximum principal stress.

4. Conclusions

The current study investigated four composite layouts to strengthen a historical masonry vault in Erzurum province. The models were compared in terms of maximum principal stress, i.e., tensile stress, and their effectiveness was evaluated.

According to the results of the investigation of the linear behaviour of masonry vaults, the retrofitting arrangements did not change the distribution of tensile stresses but limited the maximum tensile stress amount.

Intrados reinforcement arrangements are more effective than extrados. In addition, the intrados-straight retrofit arrangement is the most effective, with a *PE* of 24%. On the other hand, extrados strengthening arrangements showed very low effectiveness. With this study's results, where the masonry's linear behaviour is taken as a reference, data parallel to the literature have been obtained. On this basis, the effectiveness of various reinforcement arrangements has been investigated, and recommendations have been given. Further research, such as the determination of composite placement, efficacy of different materials and nonlinear behaviour of reinforced models, are important aspects of the subject that must be addressed.

Determining the optimum composite placement by revealing their effectiveness experimentally is further research suggests that will significantly contribute to the literature.

A study comparing composite materials and determining the most effective material can contribute to the literature. While making this comparison, it may be critical for strengthening recommendations that the results are presented with experimental and non-linear analyses, taking into account that the bond that different materials will form with masonry may be different. On the other hand, it is foreseen that a well-structured formulation is needed to determine the amount of material to be used to make a fair comparison of composite materials with different thicknesses, fibre ratios and stiffness.

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Conflict of Interest

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Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.