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Reinforcement Of Historical Arch Structures with CFRP Fabric Using Finite Element Method

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Abstract – Stone arches have been among the important structures in architecture and engineering throughout history. However, they can be damaged over time due to environmental impacts, conditions of use and natural disasters. Therefore, modern strengthening methods are needed to increase their durability. Carbon Fiber Reinforced Polymer (CFRP) fabric offers an effective solution for strengthening stone arches due to its high strength, light weight and corrosion resistance. In this study, CFRP applications were performed on a stone arch model with a length of 478 cm, a width of 40 cm and a span of 420 cm. Four different models without CFRP, 15 cm single strip, 10 cm double strip and 5 cm triple strip CFRP were created in the analysis using ANSYS program. Roman mortar was used between the stones and 0.1 mm epoxy was used as CFRP adhesive. Within the Finite Element Model (FEM), the application steps of 0.2 mm thick CFRP fabrics are described in detail. The results show a significant increase in the durability of stone arches reinforced with CFRP and that there are key points to be considered in the application.

Keywords - CFRP fabric, Ansys Workbench, stone arch, Retrofitting, Historic arch

I. Introduction

Stone arches have historically held an important place in architecture and engineering. Although they are strong and aesthetically appealing structures, stone arches can deteriorate and weaken over time due to various environmental factors, usage conditions, and natural disasters. In such cases, modern strengthening techniques are required to enhance their durability and extend their service life [3].

Carbon Fiber Reinforced Polymer (CFRP) fabric is one of the most innovative and effective materials used in the strengthening of stone arches. With its superior properties such as high strength, low weight, and resistance to corrosion, CFRP fabric enables the preservation and rehabilitation of stone arches that carry significant historical and architectural value [6].

In this study, the strengthening process of stone arches will be carried out using the ANSYS software. The steps involved in the application of CFRP fabric will be explained in detail. Tests and results obtained after the strengthening process will be evaluated, and the advantages and limitations of the method will be discussed [5].

As a result, critical considerations and recommendations for the successful implementation of CFRP fabric in stone arch reinforcement will be presented. In this context, it will be emphasized that CFRP technology offers a significant contribution to the preservation and sustainability of all stone arches, especially historical structures [3]

This study provides a comparative analysis of the effects of different CFRP strip configurations on total deformation in historical stone arch structures. Four distinct CFRP applications carried out under constant load were systematically evaluated in terms of deformation values. The impact of strip number and placement on structural response was revealed through numerical data. In the modeling process, mechanical properties of materials such as limestone, Roman mortar, and epoxy were taken into account, adopting a finite element approach compatible with historical stone structures. The results confirm the structural performance impact of geometry-dependent variables in CFRP applications through quantitative validation.

II. Materials and Method

The strengthening of stone arches in Turkey holds great importance in terms of preserving historical and cultural heritage. Stone arches may deteriorate and weaken over time due to various environmental factors, usage conditions, and natural disasters. In such cases, modern reinforcement techniques are required to enhance the durability and extend the service life of these structures [3].

In this study, the strengthening process of stone arches will be carried out using the ANSYS software. Following the reinforcement process using CFRP fabric—an innovative and effective material—the performed tests and obtained results will be evaluated, and the advantages and limitations of the method will be discussed [5].

The arch shown in Figure 1 was modeled based on limestone and Roman mortar. Limestone, due to its high compressive strength, structural stability, and low elastic deformation capacity, can provide long-term performance in load-bearing systems [4].

However, since the porous and natural surface of limestone can hinder the adhesion of epoxy-based adhesives, surface cleaning, drying, and, if necessary, light roughening must be performed prior to application. When proper surface preparation is achieved, CFRP strips can be successfully bonded to limestone using epoxy, significantly increasing the rigidity of the structural element. This assumption allowed the modeling of contact surfaces in a simplified manner. Although surface interactions are more complex in real-world applications, stiffness and deformation comparisons were taken as the main basis within the scope of this study. Thus, the structural impact of CFRP application has been evaluated more clearly.

The first of the modeled arches will be strengthened with a single 150 mm wide CFRP fabric strip, while the number of CFRP strips in the subsequent two arches will vary as 2 strips of 100 mm and 3 strips of 50 mm, respectively.

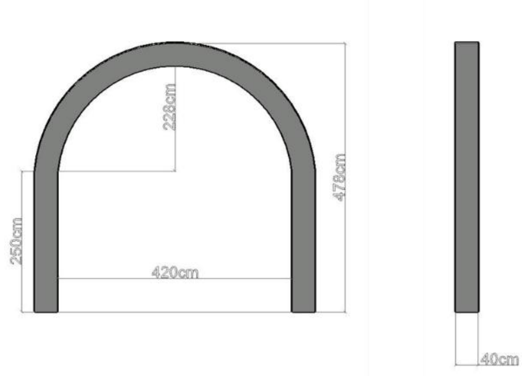

Fig. 1 The dimensions of the reference arch

A. The dimension of the CFRP sheets

Detailed views of the unreinforced reference specimen and the other three CFRP-applied arches are presented below. In the first arch, a single 150 mm wide CFRP strip was applied; in the second arch, two 100 mm wide strips; and in the third arch, three 50 mm wide strips were used. A 10 mm thick layer of Roman mortar was modeled between the stones, and 0.1 mm of epoxy was used as the adhesive for the CFRP application. The thickness of the CFRP fabric is 0.2 mm.

Table 1. Mechanical Properties of Materials

Material	Elastic Modulus, E (GPa)	Poisson's Ratio, ν	Reference
Roman Mortar	3.1 MPa	0.18	[2], [3]
Natural Stone (Limestone)	65,000 MPa	0.18	[6], [1]
Epoxy Adhesive	3,000 MPa	0.35	[4], [5]
CFRP Fabric (0.2 mm)	1,050 MPa (in fiber direction)	0.27	[4], [5]

As shown in Figure 2, each model exhibits distinct differences in terms of geometry and material configuration. The distribution of different CFRP strip configurations over the arch has directly influenced the deformation behavior of the load-bearing system. The mechanical properties of the Roman mortar, limestone, epoxy, and CFRP fabric used in the application are summarized in Table 1, and the finite element analysis was conducted based on these values.

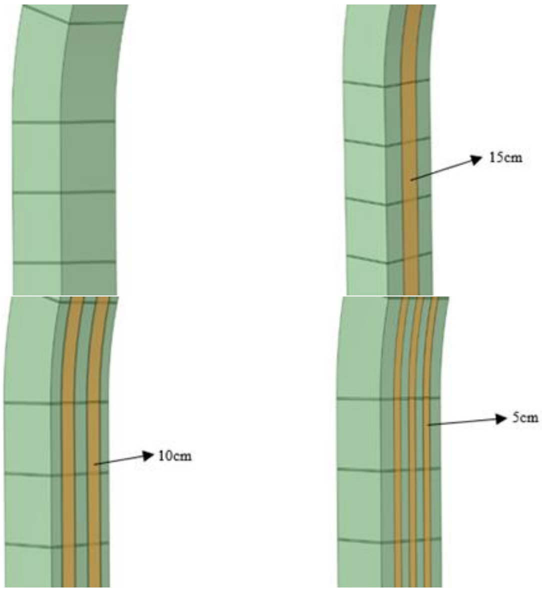

Fig. 2 Dimensions of CFRP fabric applied to the arches

B. CFRP strengthening procedure

After selecting a reference structure for strengthening, the CFRP fabric was applied in three different configurations, as illustrated in Figure 2. The finite element analysis of the model was conducted using ANSYS Mechanical software, and an automatic mesh was applied to the geometry. For the meshing process, the "Program Controlled" settings defined by the software were preferred. A combination of quadrilateral and triangular elements was used with an approximate element size of 6.454e–002 m under the default settings. The mesh quality was adjusted to ensure a uniform distribution over the geometry and to provide sufficient density to accurately represent local deformations.

As shown in Figure 3, the reference model without CFRP reinforcement was meshed with 29,062 elements and 142,984 nodes, with an average element size of 4.6e–002 m. The ANSYS Mechanical Program Controlled algorithm was employed in the model. The mesh elements were automatically generated in accordance with the arch geometry, and higher mesh density was achieved in areas close to the curved regions.

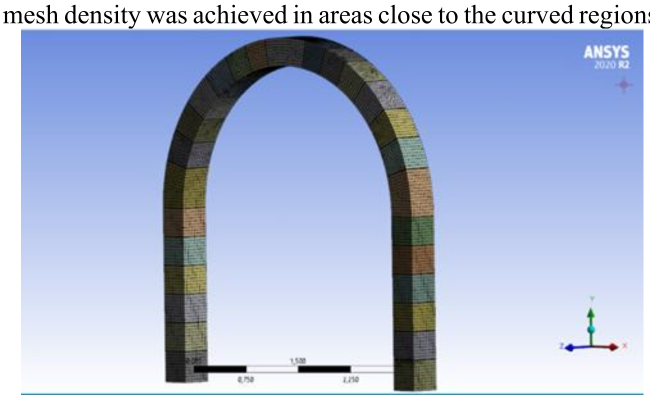

Fig. 3 Mesh model of the reference arch

The arch with a single 150 mm CFRP strip, shown in Figure 4, was modelled with 27,259 elements and 136,603 nodes, with an average element length of 4.643e–002 m. In this arch, the automatic meshing method within the ANSYS environment was employed. The element distribution was adapted by the software according to the geometry, and a denser mesh was applied in regions close to the curvature of the arch.

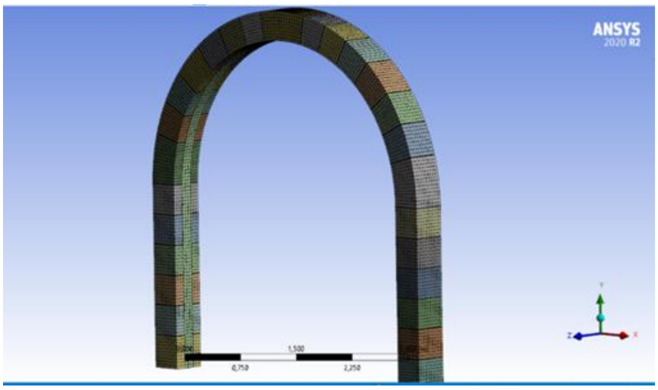

Fig. 4 Mesh model of the single sheet arch

The arch with two 100 mm CFRP strips, shown in Figure 5, was meshed with a total of 27,719 elements and 137,041 nodes. The element size was defined as approximately 4.6609e–002 m. In this mesh configuration, which was generated using ANSYS's built-in automatic meshing system in accordance with the geometry of the structure, a higher resolution was applied in areas near the curvature of the arch.

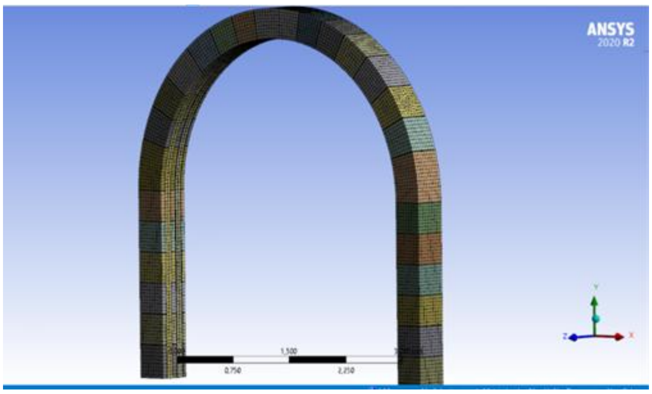

Fig. 5 Mesh model of the two-sheet arch

The arch with three 50 mm CFRP strips, shown in Figure 6, was modelled with 27,540 elements and 139,041 nodes, featuring the smallest element size among all models at 4.5537e–002 m. In this model, the "Program Controlled" option of the ANSYS Mechanical software was also utilized. The elements were automatically generated to conform to the model geometry, and denser meshing was applied in regions close to the curvature of the arch.

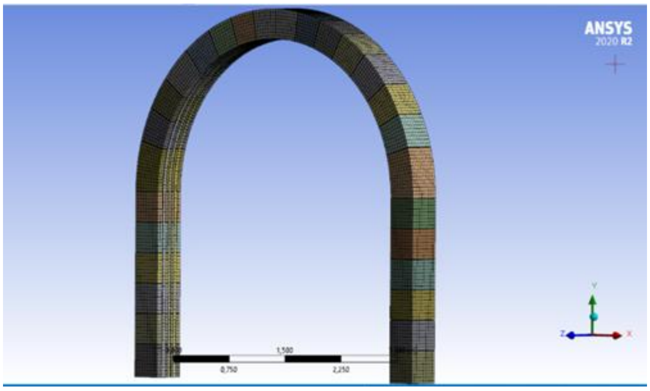

Fig. 6 Mesh model of three-sheet arch

C. Analyses

The finite element analyses conducted in the ANSYS environment were performed to comparatively evaluate the deformation behaviour of four different arch models. A vertical load of 10,000 N was applied to the apex of each model, and the total deformation values under this load were examined.

As shown in Figure 7, the unreinforced arch, which was considered as the reference model, exhibited a maximum total deformation of 0.0010141 m. This value represents the highest deformation among the four models. The deformation occurring at the crown of the arch indicates that the elastic limits of the stone material under the applied load were exceeded, and the structural stiffness of the arch was insufficient. When the load is kept constant at 10,000 N, this level of deformation reveals a critical weakness in the load-bearing integrity of the arch.

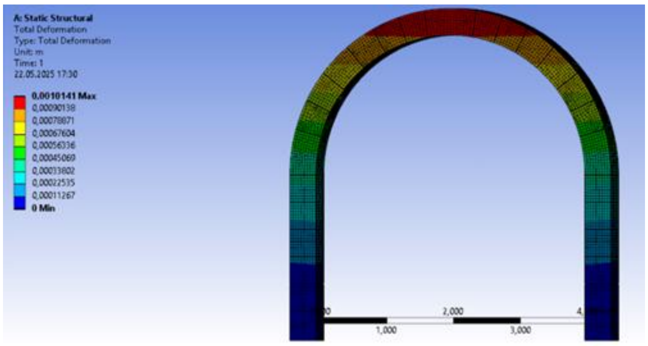

Fig. 7 Total deformation image of the reference model without CFRP

In the second model shown in Figure 8, a single 150 mm CFRP fabric strip was applied, and the resulting maximum total deformation was recorded as 0.0010005 m. The application of a single CFRP strip proved effective in increasing the stiffness of the arch, resulting in a more controlled distribution of deformation across the structure. However, the deformation remained at a moderate level, with relatively concentrated intensities observed particularly in the upper regions of the arch.

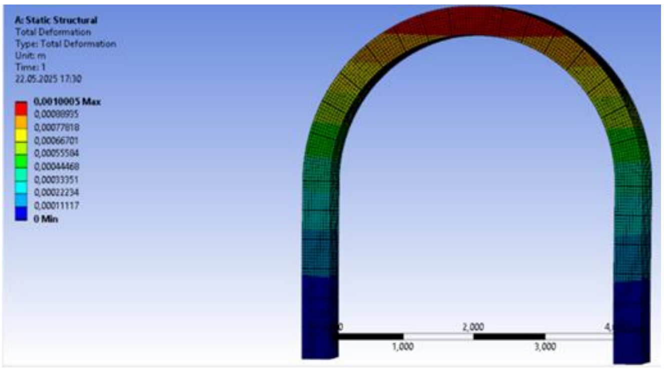

Fig. 8 Total deformation image of the arch with one CFRP strip

In the third model shown in Figure 9, two 100 mm CFRP strips placed symmetrically resulted in a maximum deformation of 6.4493e–5 m. The dual-strip application significantly increased the deformation resistance of the load-bearing system and provided a more balanced load distribution. The overall elastic behavior of the structure was observed to be more stable in this model.

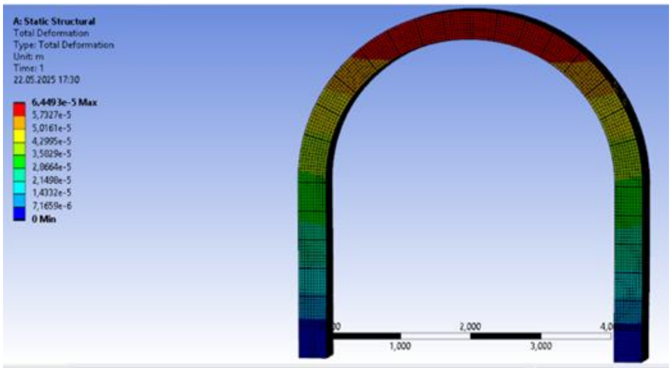

Fig. 9 Total deformation image of the arch with two CFRP strips

In the fourth model shown in Figure 10, three 50 mm CFRP strips were applied, and the maximum total deformation was recorded as 7.3719e–5 m. This value corresponds to a 92.73% reduction compared to the reference model and represents the lowest deformation among all the models. The homogeneous distribution of the strips along the arch enabled the load to be spread over a wider area, maximizing the structural rigidity. These results clearly demonstrate that not only the quantity of CFRP but also the positioning of the strips significantly affects structural performance.

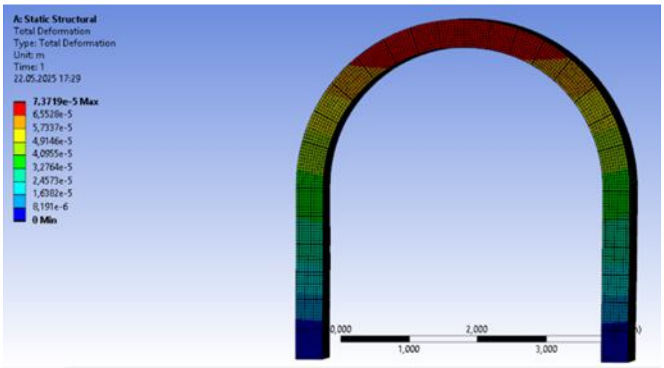

Fig. 10 Total deformation image of the arch with three CFRP strips

III. Results

The analyses conducted within the scope of this study revealed that strengthening stone arches with CFRP fabric provides a significant improvement in structural performance.

According to the results, the application of three 50 mm CFRP strips demonstrated the most effective performance. In this configuration, the total deformation value remained at the lowest level compared to the other models.

IV. Discussion

Increasing the number of strips and optimizing their placement geometry contributed to the reduction of deformation on the arch and enabled a more homogeneous load distribution. This improvement is not only related to the increased surface area of CFRP but also to the more comprehensive structural support provided under loading. Therefore, it is concluded that in CFRP applications, not only the quantity of material but also the layout geometry must be carefully designed.

In the preservation and restoration of historical structures, interventions using lightweight and high-strength materials such as CFRP fabric are highly advantageous, as they enhance structural performance without compromising the original character of the building. However, attention must be paid to factors such as adhesive selection, surface preparation, and fiber orientation during application.

V. Conclusion

For future studies, it is recommended to test different CFRP layout configurations, material thicknesses, and alternative adhesive types.

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