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Experimental and Analytical Study of the Effect of Skewed Angle on the Bearing Capacity of Semi-circular Brick Vaults

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ABSTRACT: Covering spaces has always been one of the main issues in architectural engineering. Barrel vault is one of the cover types used in traditional structures. In this paper, the effect of skewed angle on the bearing capacity of a semicircular brick vault has been examined by the experimental and numerical study. The Experimental studies have been performed in two parts: determining the properties of materials and determining the bearing capacity of the vault. Due to laboratory limitations, scaled models of materials and structures are made used. The loading of the specimens is the gravitational force with a constant rate in the middle of the span is assumed to be displacement-control. In the following, the nonlinear finite element model related to the barrel vault is developed and validated based on the Willam-Warnke failure criterion parameters. Finally, to investigate the behavior of skewed semi-circular vaults the different angles and aspect ratios is studied by analytical and parametric models. The important behavioral parameters studied in this research are failure load, maximum displacement, and also the behavioral mechanism of skewed vaults in comparison with non-skewed vaults. The results indicate that in all models, the skewed vault has a lower bearing capacity than the non-skewed vault. The maximum drop in bearing capacity due to skew occurs up to the skewed angle of 30 degrees and for larger skewed values, the sensitivity of the structural behavioral parameters to skew decreases. So that for the vault with the aspect ratio of 0.5, with an increase in the angle of skew from zero to 30 degrees, the bearing capacity of the vault decreases 58% and 18.74 for increase from 30° to 45°.

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1- Introduction

Covering spaces has always been one of the most important concerns of architecture since ancient times. A vault is a structural element used for covering spaces. This structure is practically obtained by extending an arch in depth. It is obvious that the shape of the vault depends on the geometrical shape of the arch from which it is constructed. Historical brick arches in Iran have various names based on their unique geometry. Examples include semi-circular arches, four-centred arches (in three types: Raised, ordinary, and drop), and raised pointed arches (in three types: Raised, ordinary, and drop) [1]. A semi-circular vault, which is itself made up of several semi-circular arches, is a half-bearing and half-decorative vault that can be seen in most historical sites. If the piers of the vault are not parallel to each other, or in other words, if they are not facing each other, the vault used to cover this space is skewed vault. In this type of vault, an angle is created between the edge of the vault and the vertical line, which is called skew angle (α). Figure 1 schematically shows a skewed semi-circular vault.

In recent years, numerous researchers have studied and investigated the structural and seismic behavior of this type of building, and a summary of their findings is presented below. Caro and Morales (2007) [2], Sarhosis et al. (2014) [3], Forgács et al. (2017) [4], Forgács et al. (2018) [5], Hejazi and Sadeghi (2022) [6], and Mahmoudi et al. (2022) [7] are among the most important studies in the field of masonry structures with a focus on brick Vaults. A review of the technical literature on Persian brick masonry barrel vault indicates that the assessment of load-carrying estimation and the effect of skewness on the behavior of semi-circular brick vaults have not been studied extensively. Therefore, investigating the impact of skew angle on the structural behavior of these historical structures is among the research challenges in this field. The main objective of this article is to provide a better and more accurate understanding of skewed brick vaults. In this paper, experimental and analytical comparisons are made between the load-carrying capacity and structural performance of skewed and non-skewed semi-circular brick vaults. The effect of the vault's aspect ratio (the ratio of the span to the vault's depth) is also considered to increase the sampling frequency. Nonlinear finite element analysis and macro analysis in the ANSYS code [8] are used for numerical analysis. The location of plastic joints, load-

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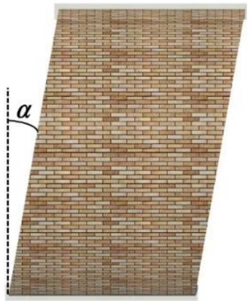

Fig. 1. Schematic of skew brick vault

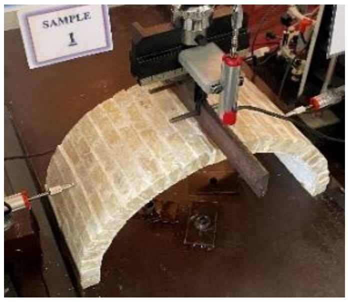

Fig. 2. Experimental model and test configuration

Table 1. Mechanical properties of materials

property	No. of specimens	value
Bulk density	3	1612.44
Young's modulus	4	829.85
Poisson's ratio [9]	-	0.17
Tensile strength	14	1.1
compressive strength	4	7.62

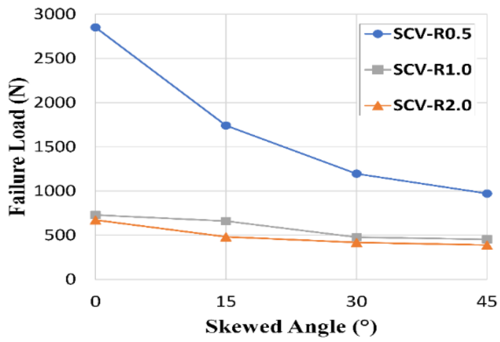

Fig. 3. failure load variations for semi-circular vault

carrying capacity under linear uniform load, stress contours of vaults, the maximum displacement of the vault crown until the moment of collapse, and the comparison of these factors in both skewed and non-skewed vaults are among the issues addressed in this article.

2- Experimental study

In this article, laboratory studies are conducted in two stages. First, the mechanical properties of the materials are extracted, which are necessary for developing the required finite element analytical model. In the next stage, laboratory studies are conducted on a Semi-circular brick vault model, and the results of these studies will be used to validate the accuracy of the finite element model.

According to British standards, strength indices for brick and plaster mortal composite vaults are determined. According to these standards, vaults are made and tested to determine their compressive strength, tensile strength, and modulus of elasticity. The mechanical properties of the materials can be summarized based on the average results obtained from laboratory samples, in accordance with Table 1.

a non-skewed brick vault model with a span (D) of 350 mm, depth (L) of 700 mm (aspect ratio of 2), and a thickness (t) of 26 mm is tested. Figure 2 shows the structural failure load test and configuration.

3- Failure criterion and validation

The Solid65 element, along with the Willam-Warnke failure criterion [10], is capable of modeling the behavior of brittle and fracture-prone materials such as masonry and brick materials. To validate the developed finite element model, the results of the experimental model were compared with the analytical model results. A finite element model with similar geometric specifications as the experimental model was created based on the assumptions of the finite element method and the failure criterion. Acceptable correspondence is observed between the results of the experimental model and the finite element model. In the correspondence in the force-displacement diagram, there is a difference of 6.05% in the failure load and 20.99% in the maximum displacement between the numerical analysis and the experimental specimen.

4- Results and discussion

The aspect ratio of the vault refers to the ratio of its span to its depth. Figure 3 shows the sensitivity of capacity and maximum displacement changes concerning the skew angle. The intensity and sensitivity of vault behavior changes in the occurrence of skewness for aspect ratios of 0.5 to 1 are much higher than other ratios. Also, it can be said that the occurrence of skewness does not have a significant effect on vaults with low depth. In other words, when the vault approaches the definition of a curve in terms of geometry.

stress distribution contours are presented for a 45° skewed vault with a 1 aspect ratio (fig. 4).

5- Conclusions

Based on the conducted studies, the following results were obtained.

1. The comparison of the load-carrying capacity of the models shows that both in the skewed and non-skewed states,

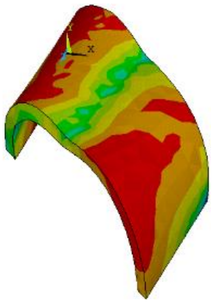

Fig. 4. Stress contour based on Willam-Warnke

as the depth increases, that is when the behavior of the vault deviates from the arch action, the load-carrying capacity increases.

2. One other effect of the skew angle is on the vertical deformation of the vault. In skewed vaults, the diameter is symmetrical, and in non-skewed vaults, it is asymmetrical.

3. The small difference between the results of laboratory experiments and finite element analyses, as well as the approximate geometric location of crack occurrence, which is similar to the maximum stress, confirms the adequacy of the Willam-Warnke failure criterion for better modeling of the behavior of masonry materials.

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