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Experimental and numerical study on effectiveness of various tie-rod systems in brick arches

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ABSTRACT

Arch-type structures have long been used to span large openings. In many historical masonry structures, the stability of the arches or pillars upon which the arches rest has been ensured by wood or iron tension members, commonly called tie-rods. Limited studies in the literature and earthquake reconnaissance reports have already verified the critical role of tie-rods on seismic behavior of arch-type structures. Iron tie-rods in many historic arches are nowadays susceptible to damages due to excessive corrosion. Similarly, strong seismic excitations or large differential foundation settlements may result in severe damage, in the form of buckling or fracturing, on tie-rods of many historic arches. In such cases, the replacement of the damaged tie-rods using a practical, reliable and effective technique is essential to retain the stability of the structure. To the best knowledge of authors, there is no published work in literature on this specific restoration work. The main objective of this study is to investigate both experimentally and numerically the viability, practicality and efficiency of five different replacement techniques proposed for the tie-rods in historic masonry arches. With this aim, six masonry arches, one reference with no tie-rod and five repaired using various tie-rod connection details, were tested under compressive load. Using the actual nonlinear properties of the masonry units and mortar, which are determined as specified by the current national specifications, a numerical study was also conducted using a commercially available structural analysis program and the test results are compared by the numerical results. In this study, the experimental results are presented in comparison with these numerical results and comments on the tie-rods used on the arches are given in consideration of the obtained results. Furthermore, recommendations are offered to solve the problems of tie-rod applications encountered in restoration works.

1. Introduction

In most of the historical structures constructed by ancient civilizations, such as bridges, churches, mosques, inns, baths, monuments and water channels, large openings have been spanned by arch-type structures. The first examples for the use of arches can be found in Sumerian underground tombs in Mesopotamia, which dates back to 3000 B.C. Other examples constructed in the same period in ancient Egypt confirm that Egyptians also had knowledge about the structural potential of arch form. Although the Sumerians or the Egyptians appear to have discovered the structural arch form, the Romans are generally accepted to have created the most effective and attractive arches.

In general, arches in historic applications have wood or iron tension members, commonly called tie-rods, between the thin and slender pillars, the main function of which is to ensure the stability of the arch when subjected to large compressive loads. As an example, Fig. 1a shows iron tie-rods used in the Basilica Cistern built in Istanbul by Byzantine Emperor Justinian I in the 6th century. Similarly, wooden or iron tie-rods have widely been used in most of the mosques built in the Ottoman period. Fig. 1b shows the use of tie-rods in the famous Suleymaniye Mosque in Istanbul built by Mimar Sinan for Solomon I in 15th century.

In the literature, there is much research associated with earthquake and wind resistant design of masonry structures, and structural behavior of those under the only vertical load [1–8]. If the masonry arches are especially taken into consideration, the study carried out by Oliveira et al. [9] reports the results from a geometrical survey conducted on 59 segmental masonry arch bridges and it was found in their study that arch thickness and physical specialties of the fill are of principal significance with respect to ultimate load-carrying capacity. Chen et al. [10] analyzed the dynamic responses of underground circular arch-type structures

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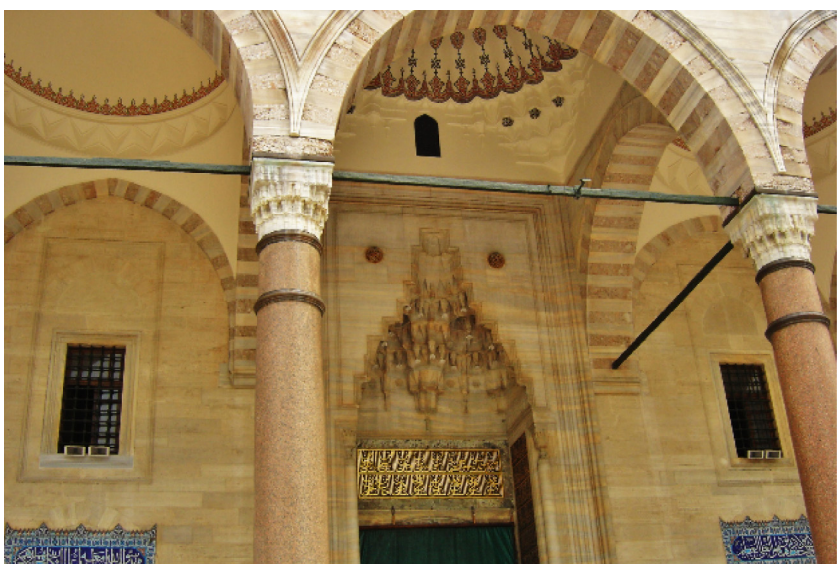
(a) Basilica Cistern in Istanbul.



(b) Suleymaniye Mosque in Istanbul.

Fig. 1. Examples of the use of tie-rods in historic structures.

subjected to subsurface conventional denotation. Sanchez-Beitia [11] examined the stability of uncracked masonry arches and their collapse mechanisms. Another critical subject investigated in recent years is the strengthening of masonry arches; Cancelliere et al. [12] investigated the strengthening of masonry arches using Fiber Reinforced Polymer (FRP) strips. They proposed a nonlinear elastic constitutive law for the masonry material. Garmendia et al. [13] considered a compatible strengthening system for the rehabilitation of stone arches. Caporale et al. [14] proposed a numerical procedure to evaluate the collapse load of multi-span masonry arch structures with externally bonded reinforcement, such as FRP, subject to debonding. Besides, some of other studies are also about the structural behavior of arched masonry structures [15–17]. Even though the studies in the literature on structural form, seismic behavior of arch-type structures and strengthening of masonry arches are quite extensive, published researches on the use of tie-rods in historic masonry arches are rather limited. The study of Lagomarsino and Calderini [18] addressed the problem of identifying the tensile vertical force of metallic tie-rods in masonry arches and vaults using the first three modal frequencies of the tie-rod, measured by means of a dynamic test. In another study of Calderini and Lagomarsino [19], an experimental study on the seismic behavior of arch-pier systems reinforced with tie-rods was carried out, with the aim of proposing innovative tie-rods characterized by lower stiffness than traditional ones. Vintzileou [20] studied the effect of timber ties on the behavior of historical masonry structures. Celik et al. [21] investigated the importance of wood and iron tension members on seismic performance of historic masonry buildings based on the three case studies from Turkey. To the best knowledge of authors, there is no published research specifically on replacement of tie-rods in the arches of historic structures and the effects of different tie-rod models on overall system behavior.

Iron tie-rods used in the arches of many historical structures are nowadays prone to large deformations mostly due to corrosion. Since these tie-rods were generally made from wrought iron, intense stratification occurs in the regions where deterioration is observed. Similarly, strong seismic excitations or large differential