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Health Assessment and Modal Analysis of Historical Masonry Arch Bridge

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Abstract. Masonry arch bridges in India indicate the heritage value of the nation. Most of these bridges had been in service for hundreds of years and yet being serviceable even today for transportation purposes indicates the robustness of the design and construction methodology. But, some of these bridges are abandoned due to its deterioration and absence of knowledge to retrofit these structures. Lack of proper maintenance and retrofitting could eventually damage the structural integrity as these structures are old enough to deteriorate and are prone to repeated weathering and unforeseen natural calamities such as earthquakes, floods, etc. In this study, a very old masonry arch bridge 'Puranapul' bridge inaugurated in the year 1578 across the river Musi in Hyderabad is considered for investigation of its health through basic visual inspection and non-destructive testing. Furthermore, the same is numerically modeled using the available finite element analysis software ANSYS in three dimensions for assessing the basic mode shapes of the structure and its behavior in different loading conditions.

Keywords: Masonry arch bridge · Heritage structure · Visual inspection · Finite element model · Nondestructive testing · Health assessment

1 Introduction

Masonry arch bridges are one of the robust and prevalent types of structures constructed for transportation practices until the early part of the twentieth century around the world among which, many of them hold a history of thousands of years of service [1]. These bridges are heritage structures which, symbolize the cultural heritage of many nations across the world. Considering the age of these structures, they must have undergone continuous deterioration due to prolonged exposure to natural or manmade loads [2]. So, it is important for us to safeguard these structures to preserve them for the next generations. A thorough understanding and precise knowledge of the structural behavior of these bridges is extremely mandatory to maintain its structural integrity and also, such studies assist in coming up with some cost-efficient retrofitting methods.

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Such, kind of heritage value always brings in awareness leading many researchers to seek fascinating experimental and theoretical understanding of these structures [3]. Hyderabad is known to be founded by Muhammed-Quli Qutb Shah, the fifth sultan of the Golconda kingdom in the year 1591 and is one of the largest cities in India located in the south-central region of the country alongside the river Musi [4]. Hyderabad is known for its heritage and most of the structures are almost 400 years old and are built-in masonry with lime as binding material largely. In this study, we have considered 'Puranapul bridge' which was one of the first Masonry arch bridges constructed across the river Musi connecting the old Golconda-Karwan area and the new city of Hyderabad. This bridge was built in the year 1578 which was almost fourteen years before the foundation of Hyderabad city i.e. 1591 using sandstone as the primary material and it consists of 22 arches aligned equidistantly over an entire span length of 185 m with a width of 10.9 m and a depth of about 12.8 m above the bed of the river Musi [5] as shown in Fig. 1.

Fig. 1. Purana pul Masonry Arch Bridge (a) Side view (b) Path way used by street vendors (c) extreme arches (d) location of measurements taken for one complete arch (e) Railing wall on either side of passageway

Purana Pul arch bridge was restored two times due to heavy floods in the year 1820 and 1908 [6]. Figure 1(b) shows that the bridge is currently being used by the vegetable vendors but not used for heavy vehicular loads from the last ten years as it has not been assessed for structural stability and integrity. Figure 1(c) and (d) shows the locations which are accessible for a structural health assessment to be carried out. This study has also focused on the sizes of stones used for the construction and properties of binding material to understand its deterioration. But this research paper limits itself to the fundamental analysis of the structure based on the properties of the materials used i.e.

sandstone obtained from the site inspection. And Fig. 2 shows the schematic representation of the complete bridge consisting of all the 22 arches with varying ground levels at the ends. It also shows the dimensions in detail i.e. each arch opening is 5.9 m and its height is 10 m from the bottom earth level whereas, the arch thickness is 0.7 m and the pier thickness is 2.95 m. All these dimensions were calculated during the visual inspection of the bridge.

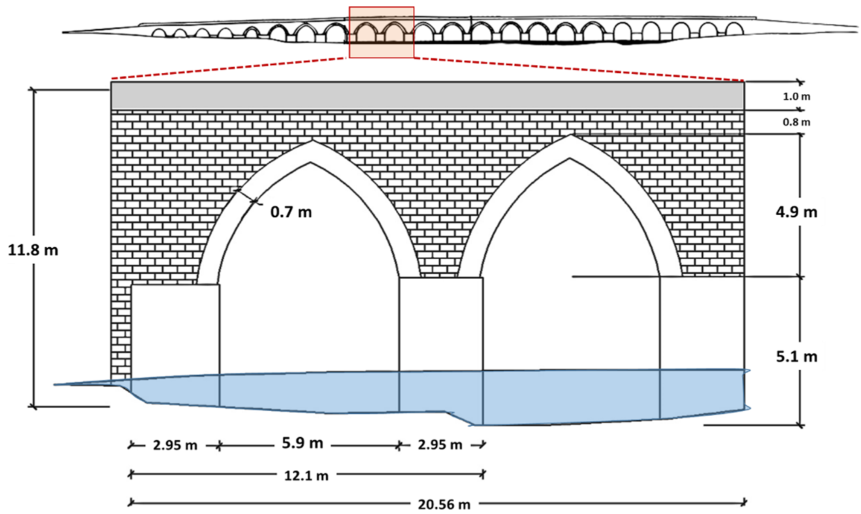

Fig. 2. Front view and componential dimensions of the arch bridge

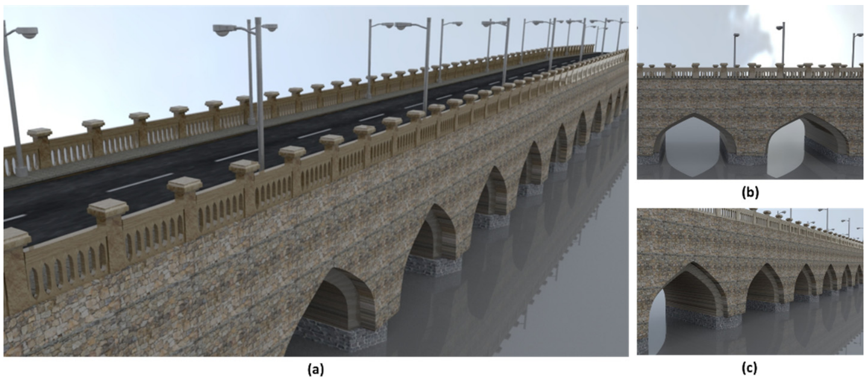

Fig. 3. Three dimensional model developed in Maya with complete detailing

To have a detailed glimpse of this bridge, a three dimensional model with complete features has been developed using Autodesk Maya and rendered using Arnold as seen in Fig. 3. There have been multiple trails for importing the same model into FEM software but had difficulties in multiple layers. So, in this paper structural health of a masonry arch bridge which is 442 years old is assessed with a keen visual inspection, and numerical analysis of the same is performed to access its current condition. The study has also attempted to know the current load-carrying capacity by its frequency. The visual inspection phase is mostly comprised of examining the materials used for construction, any structural damages to the structure, and taking accurate measurements of the entire bridge to build the numerical model, which can give a better understanding of the structure. For generating a three dimensional model for analysis, a finite element based software ANSYS is used because of its simplicity in the complex modeling, incorporation of material properties, application of loading and boundary conditions. It can be used to generate a precise numerical model and test under various loading conditions to investigate the structural integrity. The loading conditions considered for this study are gravity and live loads apart from modal analysis to find the fundamental frequency and other possible frequencies. In consequence of this numerical analysis, principal stresses, mode shapes, and total deformations for the applied loads on the masonry bridge are assessed.

2 Background

A lot of research work is being carried out on Masonry arch bridges from many decades all around the world, but yet it is still a challenge to create a realistic model [7]. Toth et al. [8] have detailed a good review of the past numerical models developed for understanding the behavior of masonry arches. The author has also mentioned that most of the 2D or 3D models of the masonry structures developed using FEM are continuum-based but masonry is fundamentally a discrete system. Few researchers have developed two-dimensional models with plane strain assumption and binding materials as a spring to understand the failure mechanism [9–11]. Other groups of researchers have concentrated on the material properties for more suitable behavior of the masonry arch bridges [12–14]. Similarly, few other researchers have developed numerical models with consideration of contact analysis between the stones for more specific deformation and sliding behavior [15]. Even though a lot of studies have been carried based on dimensions (1D, 2D, 3D), material properties (young's modulus, linear, non-linear), contact behavior (normal, shear), continuum or discrete and loading conditions still linear continuum models play a vital role in understanding the basic behavior of the masonry arch bridges, especially if the bridge does not have any structural damage. So, the current study is largely concentrated on continuum modeling and incorporation of a material model for understanding its behavior.

3 Numerical Modeling

The bridge has 22 arch spans and 185 m long, 10.9 m broad, and 12.8 m above the bed of the river. The thickness of the spandrel walls and arch is 10.7 m as shown in Fig. 2. This bridge was constructed using sandstone as the primary material for arches, spandrel walls, and abutments. Special site investigation for the substructure has not been carried. It is observed that the structural stone joints are filled with lime mortar and during the site investigation no structural damage or seepage of water from the top surface of the deck into the bridge is observed, which indicates that the structure is still in a good condition. Analysis of the masonry arch bridge is done using commercially available finite element based software in a macro modeling approach due to its minimalistic computational effort. The three-dimensional finite element modeling approach is preferred as the 3D model is generated by creating a finite element similar to the material used in construction provided with the properties such as density, young's modulus, and poisons ratio of the actual material mentioned in Table 1 used in the construction of the bridge for a better understanding of the structural behavior in ANSYS workspace. As the study is conducted on an ancient masonry arch bridge comprised of the same type of material across arches, spandrel wall, and abutments the material properties of the bridge are assumed from appropriate literature [7].

Table 1. Physical and mechanical parameters of the masonry arch bridge

Parameter	Units	Value
Compressive strength	MPa	66.9
Tensile strength	MPa	3.7
Youngs modulus	GPa	1.13
Poisons ratio	n/a	0.279
Unit weight	kN/m^3	27.5

Three dimensional finite element model developed for the complete bridge is shown in Fig. 4 with stone masonry properties. The model is tested for three types of meshes coarse (1.2 m), medium (0.6 m) and fine (0.3 m) but the results obtained were in the similar line. Current model has 31,103 nodes and 5,376 elements in total. As the bridge is symmetric in nature, an individual arch numerical model is also developed and analysis has been carried for modal and gravity analysis.

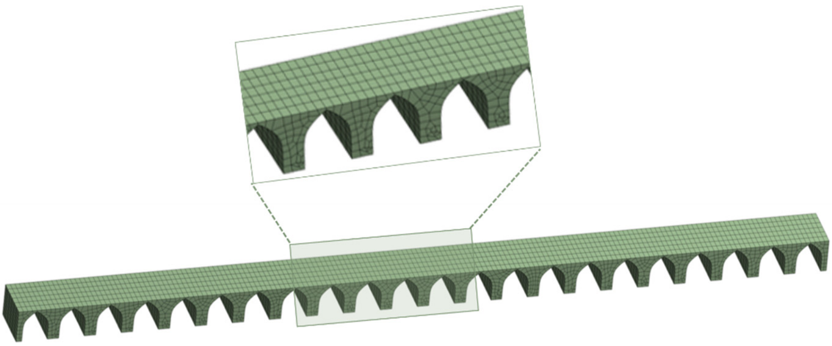

Fig. 4. Finite element model of the bridge with meshing

4 Numerical Analysis and Results

Majorly numerical analysis is done for three cases of which one is gravity analysis to understand the scale of deformations for the self-load and live load along with the maximum permissible stresses and strains. Secondly, modal analysis is carried out to know the longitudinal and transverse mode shapes with their respective frequencies. Lastly dynamic analysis is done to understand the seismic response with the foundations of the bridge being fixed. As this bridge consists of 22 uniform arches located equidistantly along its entire span to perform the numerical analysis on such kind of huge structures there is a need for high computational power, hence due to lack of high computational power, the analysis is done in a macro modeling approach as stated in a relatable literature [16] with a descent meshing size to obtain satisfactory results.

4.1 Gravity Analysis

On the application of the earth's standard gravitational force uniformly over the deck of the bridge along the negative y-direction, the following results were obtained, the total deformation of the bridge tends to be maximum at the centers of all the arches with a value of 0.14018 mm deformation in the negative y-direction and minimum at the two end surfaces and foundations of the bridge with zero deformation as shown in the Fig. 5.

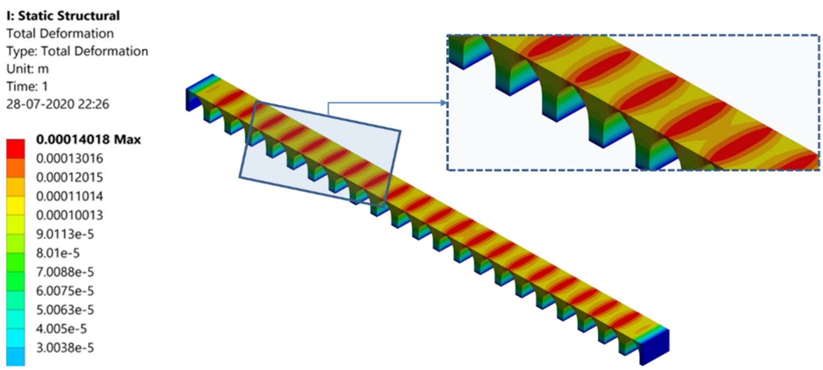

Fig. 5. Total deformations of the bridge due to its self-weight

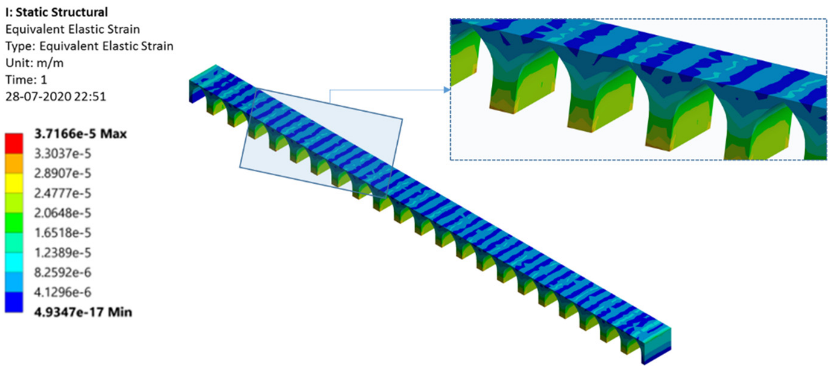

Fig. 6. Equivalent elastic strain distribution over the bridge due to its self-weight

Figure 6 shows the equivalent strain distribution all over the bridge and maximum strain is observed to be 0.03716 and at the foundation level and reentrant corners, whereas the minimum strain is observed exactly on top of the piers projected to the passage way surface as seen in the figure. Whereas Fig. 7 shows the equivalent stress distribution over the bridge and behavior is very much similar to that of strain. The maximum stress is observed to be 4.17e5 Pa at the corners of the foundation and minimum stress is observed exactly on top of the piers projected to the passage way surface as seen in the enlarged figure.

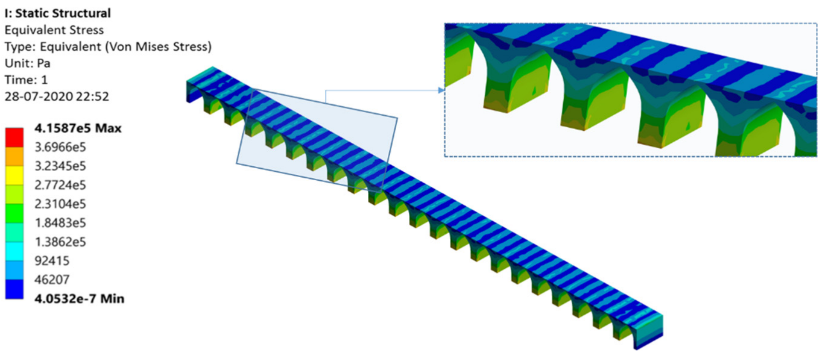

Fig. 7. Equivalent stress distribution over the bridge due to its self-weight

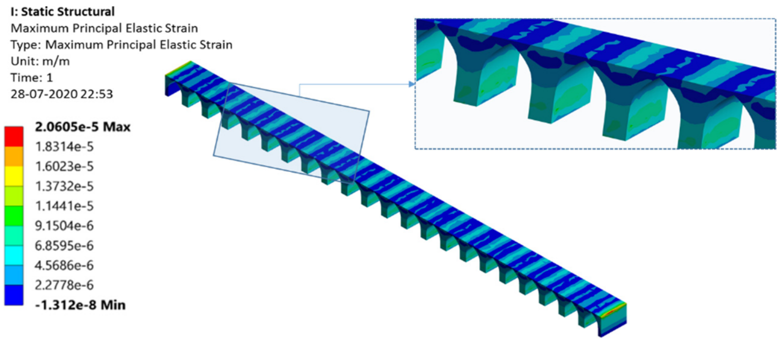

Fig. 8. Maximum principal elastic strain distribution over the bridge due to its self-weight

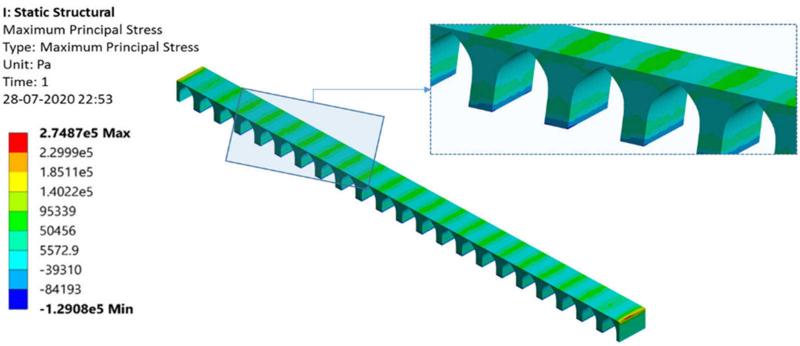

Fig. 9. Maximum principal stress distribution over the bridge due to its self-weight

Maximum principal elastic strain and maximum principal stress are shown in the Fig. 8 and Fig. 9, and the obtained results show similar behavior of the elastic strain and elastic stress.

4.2 Modal Analysis

Modal analysis is performed to understand the behavior and characteristics of the Masonry arch bridge, which are vital when a structure is subjected to dynamic loads [17].

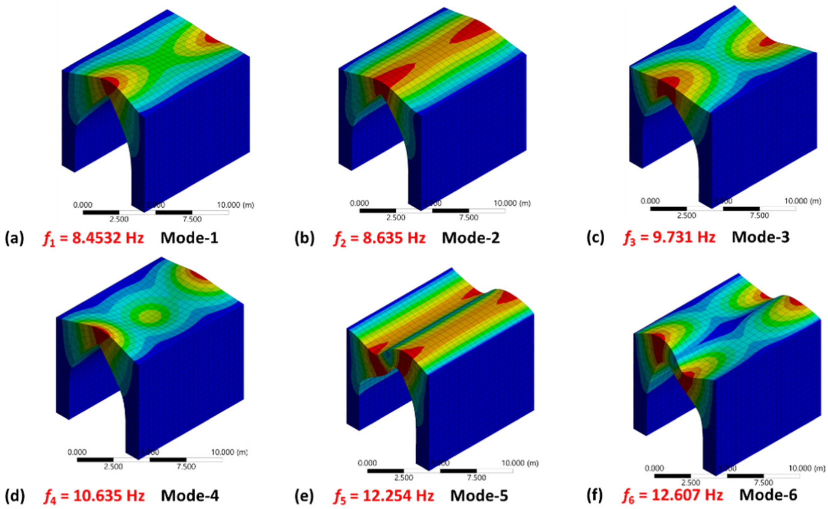

Fig. 10. Natural frequencies and mode shapes determined by finite element method of single span

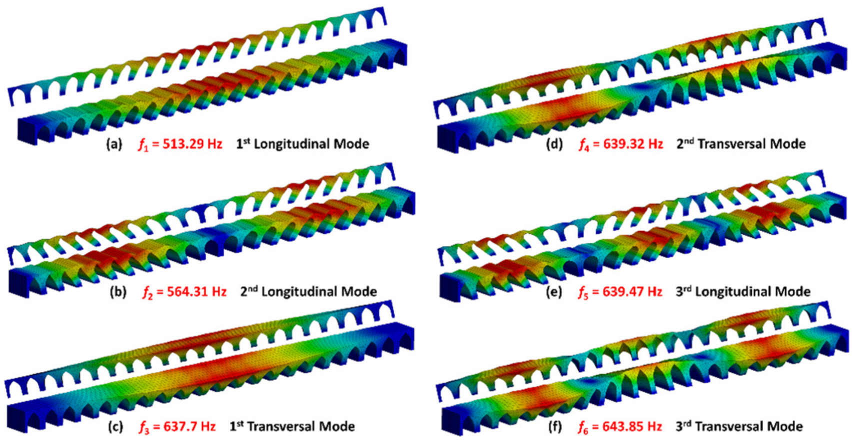

Fig. 11. Natural frequencies and mode shapes determined by finite element method for complete bridge

Figure 10 shows first six mode shapes and respective frequencies obtained from modal analysis. Boundary conditions are similar to that of gravity analysis. The frequencies obtained show the range of frequencies starting from 8.45 Hz to 12.6 Hz obtained for single span and Fig. 11 shows the first six modes of complete bridge. Frequenices are found to be higher than usual due to its size and continuum modeling. Figure 11(a) shows the first fundamental frequency 513.29 Hz in longitudinal mode and Fig. 11(c) shows the first transverse mode of frequency 637,7 Hz. Total six modes have been presented with first three longitudinal and first three transversal modes. The range of frequency are observed to be 513.29 Hz to 721.47 Hz for the first ten mode shapes and they are equally divided in to longitudinal and transversal modes shapes due to the symmetry of the structure. Modal analysis has also been carried for the model with only bottom fixed and obtained frequencies range from 483.13 Hz to 656.92 Hz. When the same is done for single arch masonry structure the frequencies of the first ten mode shapes ranged from 318.06 Hz to 1933.3 Hz.

4.3 Dynamic Analysis

The bridge is analyzed for seismic behavior to know the maximum deformation. As the Purnapul stone masonry bridge is located in the earthquake Zone-II according to IS 1893:2002, which has the zonation factor of 0.10 i.e. maximum horizontal acceleration that can be experienced by the structure in this zone is ten percent of acceleration due to gravity. To simulate the dynamic loading conditions for understanding the seismic behavior, the bridge was subjected to lateral accelerations that, were recorded on 21st Jan 2001 in Bhuj, India which was, one of the major earthquakes with a magnitude of 7.7 M_w and PGA of 0.6 g [18] causing much damage to short structures than compared to the taller ones. The ground acceleration is applied to the model in both the directions to know the maximum possible deformation of the bridge. Figure 12 shows the maximum deformations when the dynamic analysis was carried out and the maximum deformations were found to be very minimal 1.4×10^{-6} m and 6.14×10^{-8} m in x and z directions respectively. There are two major reasons for the negligible deformations, the first one would be due to the continuum modeling and the second one is due to its lesser height. So the structure is quite adequate for lateral loads also, but more precise modeling and detailed material properties can predict more probable behavior.

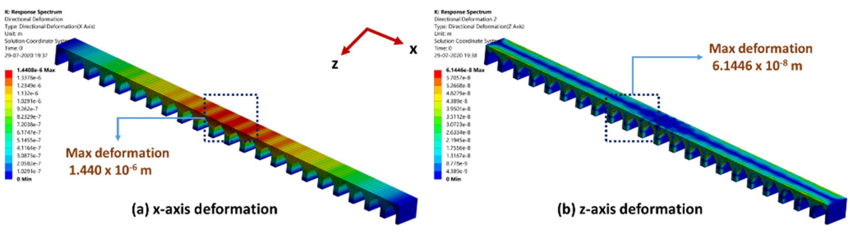

Fig. 12. Maximum deformations of the bridge for the Bhuj Earthquake ground motion in both the directions.

5 Conclusions

A 442-year-old Purna pul stone masonry bridge with 22 arches was first visually inspected and based on observations, structural analysis has been carried using the finite element method for static, dynamic loads and to investigate the response of the structure, as it was abandoned from past ten years. Currently, it is being used by street vendors which could probably affect the structural stability and functionality. To the author's knowledge, structural load carrying capacity or any other related tests have not been performed to qualitatively assess the structural stability. So, an attempt is made to understand the minimal nature of the structure and its stability. And based on the numerical analysis carried for static and dynamic loads, the current configuration of the stone arch bridge is adequate to take its self-weight and live loads coming from the vehicular traffic. As expected maximum deformations are observed to be at the middle portion of the arch and principal stresses show that they are very much in the permissible limit. Stone piers are also found to be stronger based on numerical analysis. Numerical modeling and analysis are always considered to be a very effective tool in assessing the structural health of the current heritage structures for prospective conservation and preservation. The quality of the numerical analysis is always higher and nearer to the insitu behavior if non-destructive testing results are incorporated in the numerical model. In the future, the work will be extended by incorporating the material properties in the numerical model and comparing them with the vibrational studies.

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