BEHAVIOUR OF MASONRY ARCH BRIDGES: A REVIEW

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SUMMARY

Masonry arch bridges are beautiful structures of high heritage value. These bridges are surprisingly strong irrespective of their age. There is countless number of masonry arch bridges all over the world and they play a major role in the infrastructure of many countries. Many of these bridges are subjected to different load conditions and are supposed to carry more load than they are actually designed for. The evaluation of load carrying capacity of these bridges is always important due to up gradation of the infrastructure. This paper presents a study on the developments in the analysis of the masonry arch bridges.

Keywords: *Masonry arch, FEM, prediction, strengthening.*

1. INTRODUCTION

Arch bridges are durable and economical to transfer the heavy loads and are used in railway construction from centuries. The masonry arch bridge essentially consist of wall and arch masonry, backfill, haunching and foundation [1] and is given in Fig. 1. A number of studies have been reported on masonry arch bridges varying the methods of analysis and modelling techniques. FE analysis is the latest advanced method adopted for the analysis of these structures. These analyses are carried out to evaluate the load carrying capacity of the bridge. Many studies look forward to identify the need of strengthening of existing masonry arch bridge when there is change in codal provisions or up gradation of the running load. As the stresses in the components increase with up gradation of load system, sometimes, the retrofitting works may have to be finalized. The possible alternative of the retrofitting can also be modelled in Finite Element Method (FEM) and its capacity can be assessed. As failure test of masonry bridge structures are costly, the analysis results are of great value and relevance. In this paper, the developments in the analytical approaches of masonry arch bridges are presented.

The published literatures are generally classified based on the type of loading and behaviour of the component materials. In general, two types of loading are being considered, namely, static and dynamic load method. In addition, some of the literatures focus on linear behaviour of materials, which is important when serviceability state is evaluated. However, non-linear behaviour is important when ultimate or failure stage is being considered.

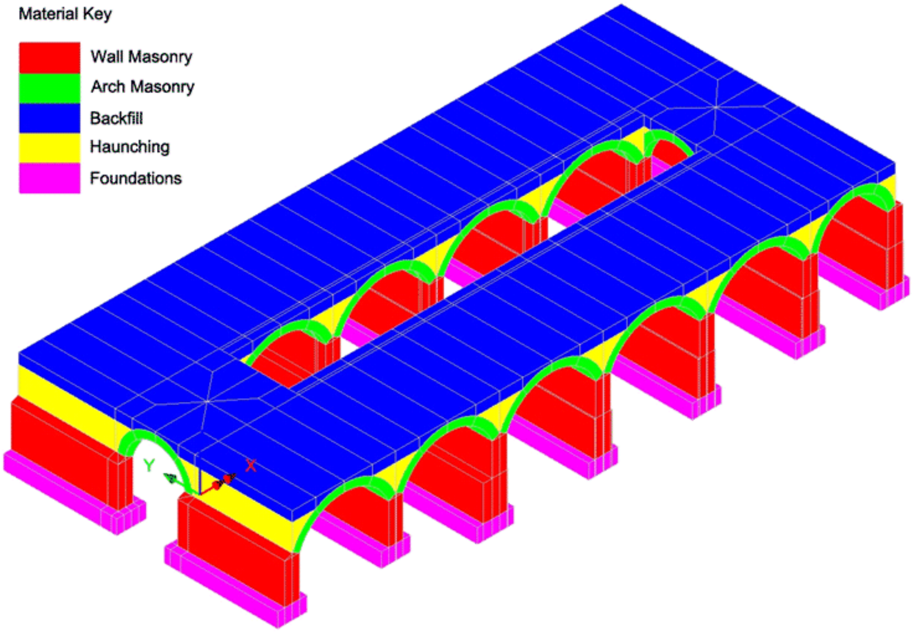

Fig. 1. *Masonry arch bridge modelled in FE software [1].*

2. LINEAR STATIC ANALYSES

Linear static method is a conventional approach of analysis of the masonry arch. In this linear behaviour of the material is being accounted for and loading is assumed to be static in nature. The major advantage of this method is in terms of computational time, which is lower than other approaches and the predictions are reasonable for the capacity evaluation at serviceability design.

Oliveira et al. [2] predicted the strength of 59 Portuguese and Spanish masonry arch bridges. The effect of properties of infill soil and arch thickness were studied. The linear static analysis was found to be an effective tool in predicting the local collapse mechanism in multi-span masonry arch bridges.

Lubowiecka et al. [3] carried out the 3D finite element analysis of masonry arch bridges using ABAQUS. The effects of incorporating the spandrel wall and soil infill were determined. Also found out that the modelling of bare arch is inadequate for detecting some of the structural damages. In spite of the geometrical non-linearity, a linear variation of the maximum principal stress was observed corresponding to support displacement of the bridge and is shown in Fig. 2.

Kaminski et al. [4] compared the capacity of the masonry arch bridge predicted using Kinematic Method (KM) and 2D FE Method. The typical damages to masonry arch barrels were also simulated by incorporating to reduce the compressive strength of the material and the elastic modulus of the joints. It is found that KM yields lower bound ultimate load bearing capacity values than FEM.

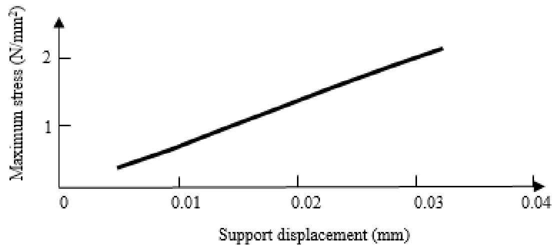

Fig. 2. *Maximum principal stress due to support displacement [3].*

3. NONLINEAR STATIC ANALYSIS

In general, all masonry arches are geometrically nonlinear structures. In this paper, nonlinearity in the material property is being referred as nonlinear problems. Fanning et al. [5] analysed masonry arch bridges using 3D FE approach using ANSYS software. SOLID65, which is an eight node brick element, was used to model the masonry and soil infill. The Drucker-Prager failure criterion was used in the analysis. The prediction based on the model was found to be in good agreement with the actual on-site data of deformation. Thavalingam et al. [6] proposed that prediction based on the nonlinear FE analysis using DIANA incorporating discontinuous deformation analysis (DDA) is realistic. Ng et al. [7] incorporated deflection-dependent backfill pressure distribution model in the analysis of Bargower Bridge. It is found that the initial deformations in the arch mobilises the variations in the lateral pressure due to soil infill. It is concluded that the passive earth pressure of the backfill influences the predicted collapse load and influence of active earth pressure is limited. Cavicchi et al. [8,9] carried out 2D FE analysis to evaluate the collapse load of masonry arch bridges. The masonry vaults and piers and soil infill were modelled. The fill is described as a Mohr-Coulomb material modified by a tension cut- off under plain strain conditions. The analysis indicated that the modelling of infill on the bridge is important in strength evaluation.

Drosopoulos et al. [10, 11] carried out a parametric investigation using non-linear FE models. It was found that the reduction of the rise causes an increase of the ultimate load, which is true up to certain value of rise corresponding to an optimum geometry [10]. The four hinge mechanism of the arch at failure is simulated using the model [11]. The 2D FE analysis carried out by Cavicchi et al. [12] highlighted the influence of transverse stress due to the soil infill on collapse load of the masonry arch bridge. Felice et al. [13] used non-linear beam elements for modelling multi-span masonry arch bridges. The arch was discretized into rectilinear beams in the analysis. It is reported that the load carrying capacity valuated based on limit analysis methods are not conservative. Pela et al. [14] carried out a FEM 3D analysis to evaluate the seismic performance of two existing masonry arch bridges (triple arched stone bridges) in Italy. Pushover analysis was carried out to simulate the inertial forces which would be experienced by the structure during the ground shaking. Based on the analysis, it was concluded that the capacity of the bridges is higher than the demand as per the seismic records of the location. The FE analysis performed by Gago et al. [15] indicated that role of infill soil in the evaluation of the bridge capacity is significant. The non-linear behaviour of the soil infill is modelled and Mohr–Coulomb yield criterion was adopted. It is also showed that neglecting the geometric nonlinear effects leads to a non-conservative estimation of the ultimate load.

The static non-linear analysis of masonry arch bridges carried out by Milani et al. [16] indicated that the difference between the ultimate load of 2D and 3D analysis is 10 percent. In the analysis of Galician bridge by Carr et al. [17], it was showed that the load corresponding to first hinge formation is between 36 and 51% of the ultimate collapse load. Domede et al. [18] carried out the structural analysis of a multi span railway masonry arch bridge using orthotropic damage model. The effects due to higher traffic loads, increase in train velocity, additional displacement of supports, ballast resurfacing and widening or reinforcement of the structure were simulated.

4. LINEAR DYNAMIC ANALYSIS

The vibrations due to vehicle impact, wind and earthquake is also important in bridge analysis. The linear dynamic analysis refers to the analysis accounting for any or all of the vibration loads. For simplicity, the material is considered to be linearly elastic obeying Hooke's law. Lubowiecka et al. [19] carried out modal analysis of 3D masonry arch bridges to determine the natural frequencies. It is showed that deformation in first mode of the bridge is influenced by modulus of elasticity of the components such as masonry vault and spandrel and infill soil. Sevim et al. [20] illustrated the importance of model calibration in the analysis of Osmanlı and Senyuva masonry arch bridges constructed across the Black Sea in Turkey. The behaviour of the structure when subjected to earthquake force is evaluated using ANSYS. The analysis results were found to be corroborating with the corresponding ambient vibration tests data of natural frequencies. Gonen et al. [21] used SAP2000 to evaluate the earthquake response of Murat Bridge in Palu state. The dynamic earthquake loads are detrimental to the masonry arch structures and hence, it is suggested that immediately after the tremor, bridge must be inspected and retrofitted.

5. NONLINEAR DYNAMIC ANALYSIS

Non-linear behaviour of the material is important in the ultimate analysis of the masonry arch bridge. Brencich et al. [22] determined the dynamic response of Tanaro Bridge. Nonlinear properties of the material were considered in the analysis. It is concluded that the transversal tie bars would not influence the structural behaviour of masonry arch bridge. Seismic time-history analysis of triple arch masonry arch carried out by Pela et al. [23] indicated strength of FE analysis to identify the vulnerable points of damage of the structure during tremor. Reccia et al. [24] used elastic-plastic material properties in the FE analysis of Venice trans-lagoon Bridge. It is concluded that the increases in the cohesion of the backfill increases predicted load bearing at ultimate stage and is given in Fig. 3.

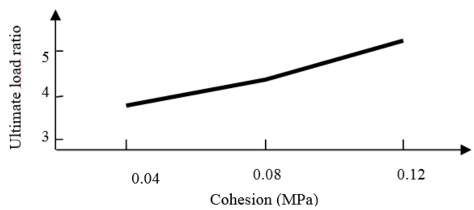

Fig. 3. *Maxi Ultimate load vs. cohesion of backfill ($\phi=30^0$) [24].*

D'Ambrisi et al. [25] presented the design criteria for strengthening masonry bridges with carbon fibre reinforced cementations matrix (C-FRCM) materials. The structure was analysed both in its original configuration and in its strengthened configuration. The non-linear behaviour of the masonry and strengthening jacket were taken into account. The analysis results showed that load carrying capacity of the original bridge was 60 percent of that required by current codes and can be improved by strengthening. Costa et al. [26] developed FE micro-model using solid elements for masonry blocks and zero thickness joint elements at their interfaces. The backfill is also modelled with solid elements connected to zero thickness joint elements in the interfaces between the infill and blocks of the arches and pavement. It is found that this procedure is allowed to simulate the formation of a hinge mechanism in the principal arch of the bridge and limiting load.

6. COMPARISON OF METHODS OF ANALYSIS

The aim of the analysis is to simulate the failure mechanism and to determine the limiting load. The four and five hinge mechanism of failure is shown in Fig. 4. The formation of the hinge causes rotation and eventually leading to the collapse of the structure. The analysis accounting for the linear strength parameters reduces the computational effort and is appropriate to determine the serviceability limits of the structure. The nonlinear analysis incorporating the effect of large deformation helps to predict the nonlinear load-deflection response accurately and is shown in Fig. 5. Kinematic method helps in evaluating the strength of partially damaged arch bridges [4]. Discontinuous deformation analysis helps in simulating the large deformation and failure mechanisms [6]. The 3D FEM approach is useful to predict the impact of damages, support widening and support yielding [18]. Dynamic analysis of bridges is helpful in health monitoring [22] and determination of mode shapes.

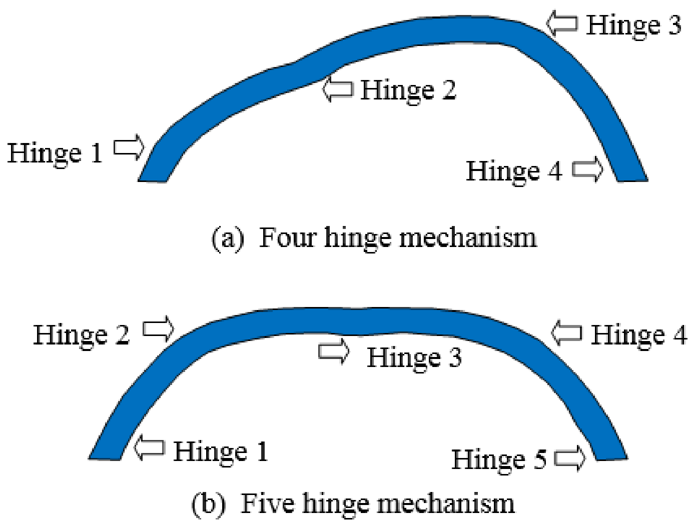

Fig. 4. *Failure mechanism of the masonry arch.*

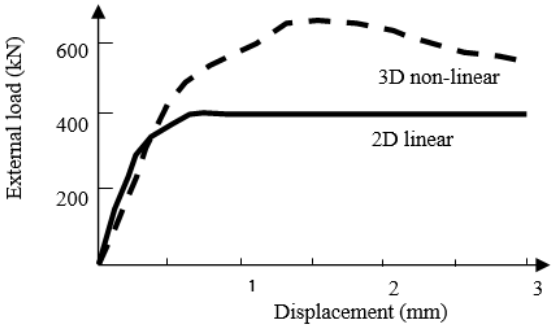

Fig. 5. *Load deformation response of single span bridge [16].*

7. CONCLUSIONS

The influence of geometry, materials and modelling techniques on the load carrying capacity of the masonry arch bridges is reviewed. The effect of soil infill on the bridge structure is also discussed. The scope for the future work includes the investigation on the influence of geometrical imperfections, support yielding and partial damages. An insight on the various fields of research on the analysis of masonry arch bridge is detailed in this paper.

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