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CAPACITY ASSESSMENT OF ANCIENT MASONRY ARCH BRIDGE: A CASE STUDY

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Most masonry arch railway bridges in the world are servicing the communities well beyond their intended design lives. However, these bridges would have undergone numerous deteriorations over the period of several decades of service life. The asset owners of these bridges are confronted with the decision over whether to continue servicing or decommissioning these bridges. Such decisions are critical from safety and economic points of views, and it can be addressed only by conducting a proper investigation of such structures. This paper presents the capacity assessment of typical in-service masonry arch bridges based on properties of masonry obtained through core testing. The bridges were modeled and analyzed for the ultimate capacity through limit state analysis method. Important parameters such as influence of backfill properties, strength of masonry, and span-to-rise ratio are discussed. The results indicate that the investigated bridges can sustain the current operating loads with a reasonable margin of safety index.

Keywords: Safety index, Failure mechanism, Parametric studies, Partial load factors.

1 INTRODUCTION

While the new construction of masonry arch bridges is uncommon nowadays, their presence as a critical infrastructure along the railways and highways attracts researchers and industry people to investigate its capacity due to increased loads from axle wheel and increased speed of trains. Investigation of such structures have been conducted since the 1930s Pippard (1948), Military Engineering Experimental Establishment (MEXE) Wang and Melbourne (2010), and it was Heyman (1969) who applied the limit analysis principle in masonry arches for the first time. However, these methods proved to be conservative approaches, while the finite element method is rarely conducted due to high computational effort. A median approach, popularly known as the limit analysis method by M. Gilbert (2007), is widely used for assessment of the masonry arch bridges. However, this method is highly dependent on the property of masonry used in the bridges, which is mostly assumed during assessment in the absence of true material properties.

Serviceability assessment of such structures were mostly carried out thought field tests using the linearly variable differential transducer (LVDT) (Boothby *et al.* 1998), and similar assessment was conducted on two masonry arch bridges with the use of the digital image correlation technique (DIC) to obtain displacement and strains of the regions of interest of the arch component of masonry arch bridges (Dhanasekar et al. 2018).

In recent times, the capacity of masonry arch bridge was assessed using the limit analysis and finite element (FE) methods, and good agreement between the results were reported (Conde *et al.*

2016, Conde *et al.* 2017, Ataei *et al.* 2016). Similar assessment of masonry arch bridge was carried out by Moreira *et al.* (2016), who reported significant influence on the capacity of masonry bridges if the piers are considered in the models. Influence on the failure mechanism of the arch ring due to support settlement was studied and reported that significant settlement changes the mechanism in the arch ring (Galassi *et al.* 2018, Zampieri *et al.* 2017). Carr *et al.* (2013) and De Felice (2009) conducted assessment of capacity of aged masonry bridges who compared the capacity at the first hinge formation and ultimate stage. The influence of geometry on the strength of arch bridges has also been studied by Oliveira *et al.* (2010), and the reported safety factor was 7.

The effect on settlement failure analysis of arch bridges subjected to local scour problem was reported by Zampieri *et al.* (2017), who observed the change of the load path due to excessive settlement in the abutment. A detailed experimental and theoretical examination of influence of backfill and spandrel wall on the collapse mechanism of a typical small scale arch masonry bridge has been reported (Melbourne and Walker 1988, Callaway *et al.* 2012, Gilbert *et al.* 2013). Their study showed that the spandrel wall did not alter the collapse mechanism; the backfill property variation influenced the sequence of hinge formation in the arch. The first hinge was formed beneath the load position followed by a hinge at the other quarter point and then in the springing point. Thompson (1995) also investigated the possible failure of spandrel wall and found that it fails by budging followed by tilting or sliding of the spandrel wall mostly on top of the quarter point.

This paper presents the assessment of two typical masonry arch bridges based on true material properties of masonry and backfill. The results present parametric study and safety index of each bridge.

2 MODEL DESCRIPTION

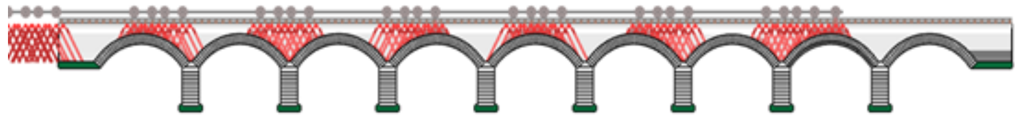
Two multi-span in-service bridges namely Bridge 1 and Bridge 2 have been considered in this case study. The geometrical details of the bridges are given in Table 1. Both bridges have uniform span, length, and width. The height of the piers varies along the length of the bridge influenced by the topography of the location, and their thickness are 1. 5 and 2m for Bridge 1 and Bridge 2, respectively. Skewness of the bridge plan was not investigated, but visual observation did not find any.

Two dimensional models were developed for each bridge using the Ring3 software, which has the capability to perform the ultimate capacity analysis for masonry arch. The structural components such as arch ring and pier were modeled as blocks, which are separated by contact element having a friction coefficient (μ) of 0.6. The backfill and spandrel wall was modeled as monolithic homogeneous material and the ballast thickness was excluded from the model. The height of the piers was kept at 3m for both the models as shown in Figure 1 (a) and (b).

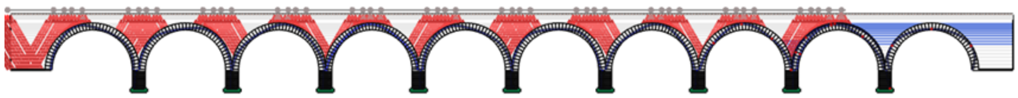
The properties of masonry used in these models are shown in Table 2, which were obtained from the core test. The property of the backfill of these bridges were studied by Westley and Parrot (2016) and used in the models.

Table 1. Geometrical information of the bridges.

Bridges	**Arch Span (m)**	**No of span**	**Rise (m)**	**Arch ring thickness (m)**	**No of rings**	**Backfill thickness (m)**	**Width of bridge**
Bridge 1	7.85	9	1.95	0.7	6	0.9	8.9
Bridge 2	13.11	10	6.554	0.92	8	1.42	8.9



(a)



(b)

Figure 1. Model development of bridges; (a) Bridge 1 and (b) Bridge 2.

Table 2. Material properties.

Material description	**Bridge 1**	**Bridge 2**
Density of masonry (kN/m^3)	21	21
Characteristic strength of masonry (MPa)	10.6	10.6
Density of fill (kN/m^3)	18	18
Internal friction angle of fill (0°)	38 (gravel)	40 (rock)

Table 3. Partial load factors.

Partial load factors	**Bridge 1**	**Bridge 2**
Fill unit weight (γ_f)	0.85	0.85
Masonry unit weight (γ_{mg})	0.9	0.9
Ballast unit weight (γ_b)	0.7	0.7
Track load (γ_t)	0.7	0.7
Masonry strength (γ_m)	1	1
Live load factor (γ_l)	1.6	1.6
Dynamic load allowance (α)	0.67	0.16

Partial load factors and dynamic load allowance given in Table 3 are in accordance with existing standards (AS5100.2 2017). The models were analyzed for different axle wheel configurations of locomotive and wagon as per existing standards (AS5100.2 2017) and RSA loading standards. Figure 2 shows a typical locomotive wheel configuration. Seven load cases—three each for locomotive (RSA 270, RSA 210, and RSA 180), wagon wheel configuration (RSA 270, RSA 210, and RSA 180), and design axle load configuration as per AS5100.2 (2017)—have been considered. For each load case, the first wheel was applied at the crown position of the arch and performed the analysis to determine the safety index. The process was repeated for the quarter and support positions. The load case, which resulted lowest safety index, is considered as the critical load case.

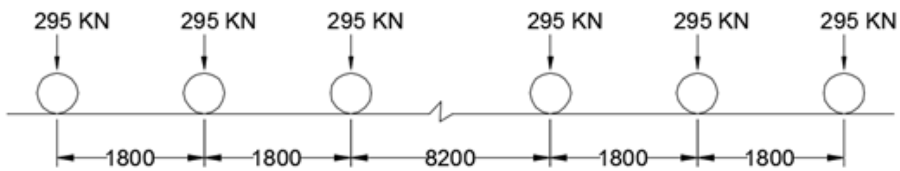
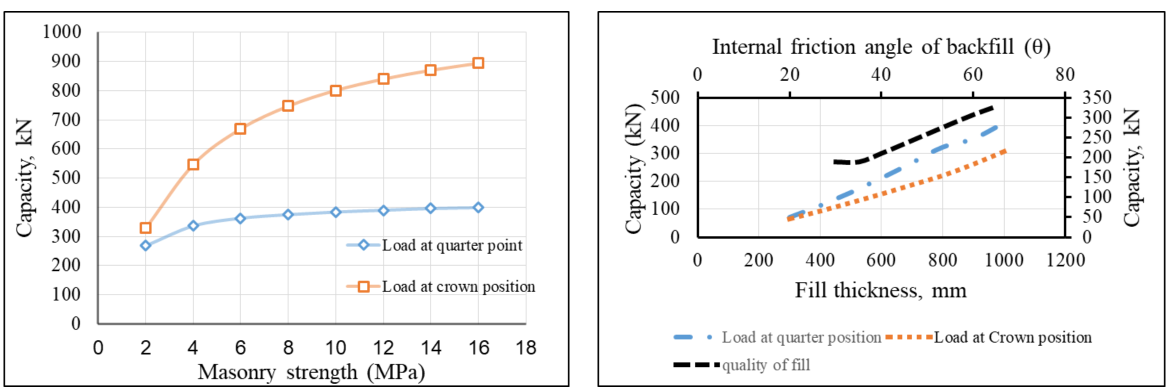


Figure 2. Locomotive axle wheel configuration (RSA 270).

However, the parametric studies have been carried on Bridge 2 under a single axle load of 300 kN to control the variation due to adjacent wheels. Important parametric studies such as the effect of geometry (*R*), which is the ratio of span (*L*) to rise (*h*); backfill property; and masonry strength have been performed. The R value was varied from 2 to 10 to study the variation in capacity for the deep and shallow arch form. The influence of the masonry strength on the capacity of the arch was studied by varying the strength of the material from 2 to 16 MPa. Similarly, the influence of the backfill was studied by varying the backfill thickness from 250 to 1000 mm and its internal angle of friction from 28 to 60 degrees.

3 RESULTS

The masonry strength significantly influences both the capacity and failure mechanism in the arch as shown in Figure 3(a). When the masonry strength is lower than 1.5 MPa, the arch fails in three hinged-mechanism, and all hinges are formed within the proximity to the point of load, but the number of hinges increased to the maximum of five hinges as the strength of masonry increases beyond 10 MPa. Similarly, both the thickness and internal friction angle of the backfill are found to influence the capacity as shown in Figure 3(b).



(a) (b)

Figure 3. Summary of results; (a) Influence of masonry strength and (b) Influence of backfill property.

The capacity of the arch decreases as the *R* value increases under a point load at the crown. However, when the point load was applied at the quarter-point, the capacity increases initially up to *R*=5 and then decreased as shown in Figure 4(a). Such variation clearly indicates that the influence of backfill on certain geometry of the arch and thus the importance of considering the true geometry of an arch during assessments. Figure 4(c) and (d) show the failure mechanism of Bridge 1 and Bridge 2 under critical load case. The safety indices of the bridges are found to be

2.1 and 4.4 by considering the actual material property but ignoring the deteriorations that have taken place.

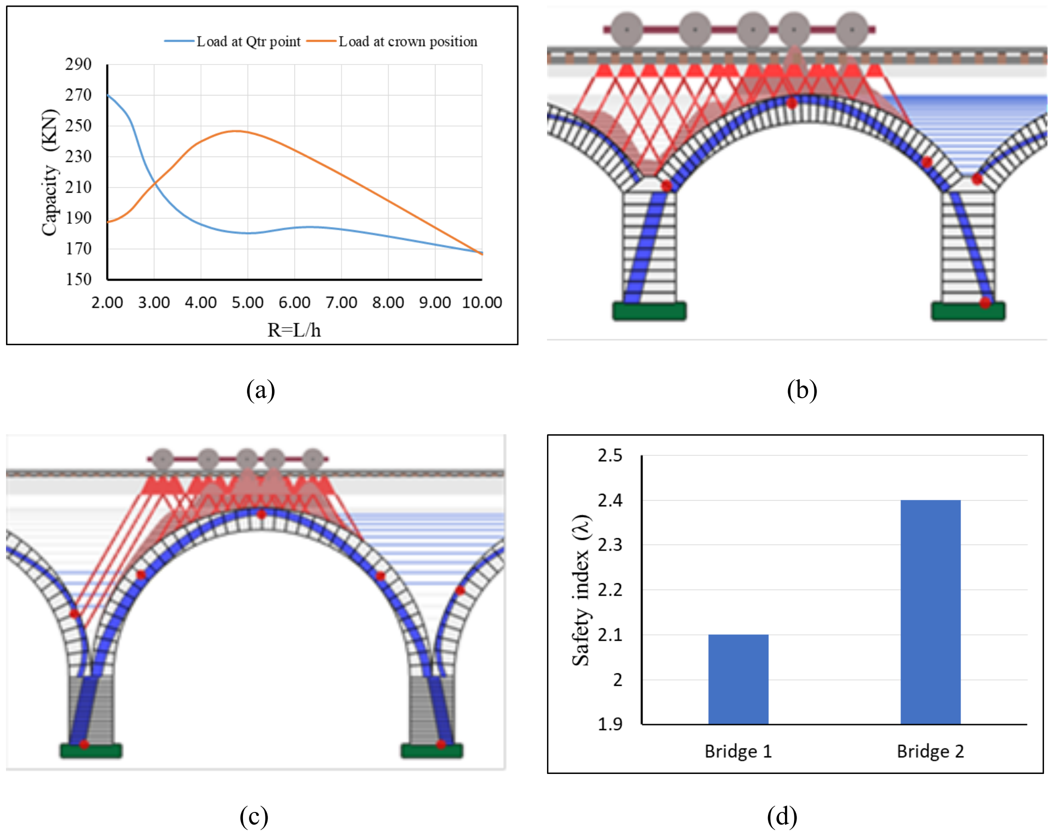


Figure 4. Summary of results; (a) Influence of geometrical shape, (b) Failure mechanism of bridge 1, (c) Failure mechanism of bridge 2, and (d) Safety index.

4 CONCLUSIONS

Ultimate capacity assessment of two typical masonry arch bridges used in railway track have been carried out to evaluate the safety index based on the material properties obtained through core testing results. The following are some of the findings of this study:

- Masonry arch bridge with pier as the main support, irrespective of shape and load conditions, enters into the mechanism with four hinges. Three hinges take place within the arch span while the fourth hinge takes place at the base of the pier.
- Strength of masonry and backfill properties are found to have significant influence of the capacity of the masonry arch bridges.
- Positioning of the wheels on the arch span and the axle wheel-set configuration were found to influence the capacity evaluation.
- The bridges under study have a reasonable capacity to withstand the present operating loads.
- The influence of backfill on the arch behavior is more pronounced when the point load is applied at the quarter-point.

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