An Examination of Backing Effects on Ratings for Masonry Arch Bridges

Muhammad E. Rahman and Paul J. Fanning

Abstract—Many single or multispan arch bridges are strengthened with the addition of some kind of structural support between adjacent arches of multispan or beside the arch barrel of a single span to increase the strength of the overall structure. It was traditionally formed by either placing loose rubble masonry blocks between the arches and beside the arches or using mortar or concrete to construct a more substantial structural bond between the spans. On the other hand backing materials are present in some existing bridges. Existing arch assessment procedures generally ignore the effects of backing materials. In this paper an investigation of the effects of backing on ratings for masonry arch bridges is carried out. It is observed that increasing the overall lateral stability of the arch system through the inclusion of structural backing results in an enhanced failure load by reducing the likelihood of any tension occurring at the top of the arch.

Keywords—Arch, Backing, Bridge, Masonry

I. INTRODUCTION

MASONRY arch bridges represent a significant percentage of bridges on the rail and road networks in Republic of Ireland. There are approximately 20,000 bridges in the Republic of Ireland and it is estimated that around 80% of these bridges are masonry arch bridges. Many of the masonry arch bridge in Ireland were built in the 16th to 17th centuries and are now carrying traffic loads far beyond those estimated by their designers. The weight of vehicles on bridges has increased steadily. European Union directives require that bridges do not constitute a barrier to free movement of goods and a 1999 directive requires that all bridges in the European economic area be capable of enabling safe passage of vehicles having a gross vehicle weight (GVW) of 40t. The minimum axle weight is specified as 11.5t [1], [2].

The behavior of masonry arch bridges are complex system whose structural response is a function of the composite masonry and mortar material, the contained fill material, backing and the interaction between these and the surrounding soil medium. The authors have attempted to evaluate the significance of the interaction between the arch and the backing. It has been found that the backing significantly affects the capacity of the arch. This study concludes that when the effect of backing is taken into account, the capacity of the arch is significantly higher. The aim of this paper to examine the effect of backing on the ultimate capacity of masonry arch bridges [1], [2].

II. FRAME ANALYSIS METHOD

This method, which uses a linear elastic analysis, is used to find the load carrying capacity of a masonry arch bridge by determining axial force and moments throughout the arch barrel. Co-existing axial force and moments throughout the arch ring are then compared to an estimate of the strength of the arch ring cross section [2], [3].

In this method, a unit width of the arch barrel is modelled as a series of straight elastic bars using a linearly elastic frame analysis routine in order to determine an admissible set of forces and moments in the arch barrel. The arch ring is divided into number of segments. The supports are considered as a rigid in the vertical direction and have elastic springs in the horizontal direction, allowing horizontal movement of the abutments but not vertical displacement or rotation (Fig. 1).
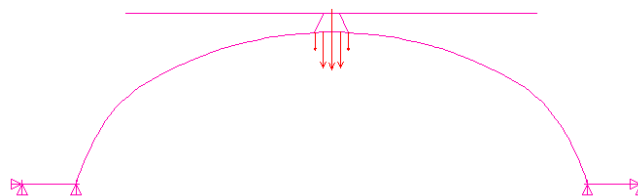

Fig. 1 2D Frame Analysis Model of Griffith Bridge

The fundamental material stiffness property used in the analysis is an effective modulus of elasticity representing the combined effect of masonry units, mortar and joints. The self-weight of the arch ring is computed and superimposed dead loads include the weight of the fill and weight of the paving material. The live load is taken as a linearly varying vertical pressure on the back of the arch ring resulting from truck axle load. Each axle load is applied over a length of 30 cm and a width of one traffic lane, or 3 m. The load is dispersed through the fill at a slope of 2 vertical to 1 horizontal. After execution of the analysis for various axle patterns, and positions, predicted axial forces and moments are checked against a strength assessment of the arch cross section.

The original strength assessment procedure specified relatively low compressive strengths and no tensile strength for masonry. The compressive strength values were confirmed, by material testing, to be conservative and have been re-evaluated following material tests in [4]. Modelling

M. E. Rahman is with the Curtin University, Sarawak, Malaysia, CDT250 98009, Miri, Sarawak, Malaysia (corresponding author phone: 60-128-5451750; fax: 60-85443838; e-mail: merahman@curtin.edu.my).

P. J. Fanning is with University College Dublin, Dublin 4, Ireland (e-mail: paul.fanning@ucd.ie).

World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:4, No:12, 2010

studies of bridges in a testing program in the US [5] and in Ireland [2], [3] have indicated that the tensile capacity of well-constructed masonry in good condition may be as high 1.0MPa. Using an ultimate strength assessment model with a ratio of tensile strength to compressive strength, specified as ß, an explicit expression for the compressive strength requirement of any cross section of an arch, of depth h, subjected to an axial load P and a moment M can be written as:

$$f_c = \frac{1}{2\beta h^2}\left[\sqrt{[ph(1-\beta)-2M(1+\beta)]^2 + 4\beta(ph)^2} - [ph(1-\beta)-2M(1+\beta)]\right]$$

(1)

Hence, at each cross section of the modelled bridge the required compressive strength f_c can be determined on the basis of the combinations of axial force and bending moment.

III. INCLUSION OF BACKING

The procedure outlined above has been implemented in the general purpose finite element software code ANSYS V5.7. Two-dimensional two noded linear elastic beam elements were used to model the bridge arches while two-dimensional four noded quadrilateral elements were used to account for the backing. The finite element of one of the study bridges is shown in Fig. 2.

Fig. 2 2D Frame Analysis Model with Backing

IV. STUDY BRIDGES

Two bridges located in the Dublin area were considered in the study. Typically the bridges were rated with and without the backing material being modeled explicitly. Each of the bridges was in good condition and the compressive and tensile strengths of the masonry in the arch barrels were set at 15MPa and 0.75MPa respectively for the purposes of determining a safe axle load on a single axle bogey.

Griffith Bridge (Fig. 3) is an elliptical arch canal bridge on the Grand Canal in Dublin. Grand Canal company built most of the masonry arch bridges of the Grand Canal during seventeenth centuries with nearest span length. The bridge is dated 1791 and was named, like most canal bridges, namely Richard Griffith.

The Griffith Bridge has a span of 9.48 m, a rise over the abutments of 2.71 m, a rise of the arch barrel at the quarter points of 2.265m, an average depth of fill, at the quarter points of the transverse road profile, between the road surface and the arch barrel at the crown, including road surfacing of 0.125

m, a span rise ratio of 3.5, and an arch ring thickness of 450mm. The arch barrel has maintained its elliptical shape with no major distortions. The foundations of the bridge were not inspected. However, from springing levels taken and the absence of any distress in the arch barrel, it can be inferred that there is no relative settlement or horizontal movement of foundations an abutment. The spandrel walls are in good condition with no separation from the arch barrel and no lateral distress [6].

The Killeen Road Bridge built in 1791 is an elliptical masonry arch canal bridge like Griffith Bridge. Located on the southwest side of the Dublin and links to Daingean road over the Grand Canal. The Killeen Bridge was named after Patrick Killeen, who was a master of the Ranger. The Killeen Road Bridge has a span of 9.29 m, a rise over the abutments of 2.646 m, a rise of the arch barrel at the quarter points of 2.35m, an average depth of fill, at the quarter points of the transverse road profile, between the road surface and the arch barrel at the crown, including road surfacing of 0.25 m, a width of 7.17 m, a span rise ratio of 3.51 and an arch ring thickness at the key stone of 0.516 m and at the springing level of 0.43m. The arch ring is constructed of limestone on the face and in the barrel, with joints about 1 cm thick. The spandrel walls are also of ashlars limestone construction, with joint thickness of approximately 1 cm [6].

Fig. 3 Griffith Bridge - Dublin

V. LOAD RATINGS

The material properties used for each of the bridges, Table 1, are based on the recommendations of Boothby (2001) and Fanning and Boothby (2001) which demonstrated close correlation between three dimensional finite element model results for these bridges compared to service load test responses.

The ratings, the maximum safe axle load on a single axle bogey, for Griffith Bridge & Killeen Bridge, for the various backing height are listed in Table 2 and Table 3 respectively. The strength demand on the components of Griffith Bridge at the maximum safe axle load, at their critical location, is plotted in Fig. 4. The maximum strength demand is 0.15x108 N/m2, 15MPa, for axle loads of 26.8 tons. In general it was found that for the single span bridges the effect of introducing backing material was to increase the safe load that could

World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:4, No:12, 2010

TABLE I
MATERIAL PROPERTIES OF MASONRY FOR FINITE ELEMENT MODELS

Bridges	GRIFFITH	KILLEEN
Young's modulus (GPa)	10	10
Density (kg/m^3)	2200	2200
Tensile Strength (MPa)	0.75	0.75
Compressive Strength (MPa))	15	15

TABLE II
ASSESSMENT RESULTS, GRIFFITH BRIDGE

Backing Height (m)	Backing Width (m)	Axle Load (Tonne)
0.0	0.0	20
0.83	0.5	26.8
1.60	0.5	30

TABLE III
ASSESSMENT RESULTS, GRIFFITH BRIDGE

Backing Height (m)	Backing Width (m)	Axle Load (Tonne)
0.0	0.0	22.5
0.83	0.5	29.5
1.60	0.5	30.7

677757 .387E+07 .706E+07 .103E+08 .134E+08
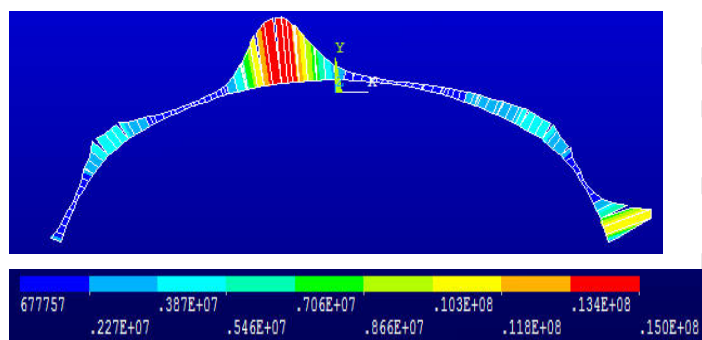.227E+07 .546E+07 .866E+07 .118E+08 .150E+08

Fig. 4 Strength demands on arch cross sections for a specific bogey location (N/m^2)

traverse the bridge. The rating of the Griffith Bridge and Killeen Bridge, in Table 2 & Table 3, increased with backing and also increased with increasing height of the backing. In the case of Griffith Bridge backing height of 0.83m yielded rating +34% higher than without backing, while 1.60m height backing yielded ratings +50% higher than without backing. In the case of Killeen Bridge backing height of 0.80m yielded rating +31% higher than without backing, while 1.5m height backing yielded ratings +36% higher than without backing. Backing has the effect of lateral stability of the arch and hence it increased ratings. It can be concluded that increasing the overall lateral stability of the arch system through the inclusion of structural backing results in an enhanced failure load by reducing the likelihood of any tension occurring at the top of the arch. The ratings analysis for Griffith Bridge and Killeen Bridge using frame analyses method indicates that backing is required for sensible load ratings.

VI. CONCLUSION

A two-dimensional masonry arch assessment procedure has been extended to explicitly include modeling of the backing material. It has been found that increasing the size of the backing increase the capacity of an arch bridge. The increase of the overall lateral stability of the arch system through the inclusion of structural backing results in an enhanced failure load by reducing the likelihood of any tension occurring at the top of the arch. The addition of structural backing between adjacent arches of multispan or beside the arch barrel of a single span could result in reasonable cost savings when compared with the cost of replacing the structure and hence increase environmental sustainability.

Existing arch assessment procedures generally ignore the backing effects. This has been demonstrated to lead to conservative assessments of safe axle loads. Given that a precise understanding of the properties of the backing in an arch bridge is not achievable, it is considered prudent that this practice is continued in the knowledge that the omitted effect is a further beneficial one.

REFERENCES

[1] M.E. Rahman, "Load rating analyses of masonry arch bridges", MSc thesis, Dept. of Civil Eng., University College Dublin, Dublin, Ireland 2002.

[2] P.J. Fanning and T.E. Boothby, "Three dimensional modelling and full – scale testing of stone arch bridges", *Computers and structures*, Vol. 79, No 29-30, pp. 2645-2662. 2001.

[3] T.E, Boothby, "Load rating of masonry arch bridges", *Journal of Bridge Engineering*, *ASCE*, Vol. 6, No. 2, pp. 79-86. 2001.

[4] P. J. Fanning and T.E. Boothby, "Load rating of masonry arch bridges-refinements", *Journal of Bridge Engineering*, *ASCE*, Vol. 9, No 3, pp 304-307. 2004.

[5] T.E. Boothby, D.E. Domalic and V.A. Dalal , "Service load response of masonry arch bridges", *Journal of Structural Engineering*, ASCE, Vol. 124, No 1, PP. 17-23. 1998.

[6] P. J. Fanning and T.E. Boothby, "A Comparative study of assessment methods for masonry arch bridges", *Seminar: Masonry Arch Bridge Assessment,* eds. A. Gonzalez & P. Finnegan, UCD, Dublin, The Institution of Structural Engineers (IRL), pp.14-24. 2002.