THE INFLUENCE OF GEOMETRY ON THE STRENGTH OF MASONRY ARCH BRIDGES

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SUMMARY

Many masonry arch bridges remain in service around the world in varying conditions. This paper presents the results of a parametric study of the geometric parameters of masonry arch bridges. The basic tool used in this study is a purpose designed non-linear finite element program which models the masonry and the spandrel fill. The paper will assist in the understanding of the behaviour of arch bridges and how their geometry influences the mode of failure. Optimum shapes are also discussed.

KEYWORDS

Arch, Masonry, Nonlinear Finite Element
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INTRODUCTION

Masonry arch bridges have been extensively studied over many centuries. Numerous computational methods have been developed but mainly using beam elements in finite element analysis. A new approach which embodies the two dimensional nonlinear finite element procedure is introduced for the progressive failure analysis of masonry arch bridges. Failure criteria normally used for plain concrete is adopted to define the failure of masonry as a material under all biaxial stress states. Nonlinear stress-strain relationships is used for masonry in compression and the elastic-brittle constitutive relationship is used when masonry is subjected to tension. The failure criteria together with the adopted constitutive relationship for masonry enable both cracking and crushing of the arch under incremental loading conditions to be analysed simultaneously. under incremental loading conditions to be analysed simultaneously. A stress redistribution scheme is employed such that results for stress distribution, cracking and crushing at any load level may be traced graphically on a computer. Finally the iterative procedure produces for the arch, the failure load and the associated collapse mechanism (if it exists). Fig.1 demonstrates a typical masonry arch bridge, the Stanwell Park Viaduct in location between Sydney and Wollongong.

Most previous analyses were focused on the ultimate capacity of an arch with a given geometry. The parametric study presented in this paper investigates the influence of the geometrical properties of an arch its structural behaviour. In particular the span/rise ratio is studied in the paper.

Fig.1 Stanwell Park Viaduct.
CRACKING AND FAILURE ANALYSIS

To model the progressive failure of masonry arches, an iterative method has been developed incorporating the non-linear finite element procedure. By appropriate modelling of the failure characteristics of masonry as a material, local cracking or crushing under loads can be simulated. Once local failure has commenced in an arch, a stress-redistribution scheme is initiated that allows for crack propagation and/or the spreading of the crushed zones under incremental loading or incremental support displacement to be determined numerically. The analysis can continue up to the collapse load. More details may be found elsewhere (Yang 1991).

For a given point of an arch, the cracking and failure analysis may be briefly explained with the help of Fig. 2 as:

(i) **Cracking in both principal stress directions.** This occurs when the state of stress is of the biaxial tension-tension type and both the tensile principal stresses are beyond the tensile-failure envelope, which is designated zone 1 in Fig. 2. In this situation the material loses its tensile strength completely.

(ii) **Cracking in one direction.** This occurs when the state of stress is of the tension-compression type and a principal stress in $\sigma_1$ direction exceeds the limiting value prescribed by the tension-failure surface (see zone 2 in Fig. 2). In this case, the material loses its tensile strength in the direction parallel to $\sigma_1$. For this failure mode, the cracked masonry may be assumed to retain some shear stiffness due to interlocking/friction on the rough crack surface. For the case of a principal stress in the $\sigma_2$ direction exceeding the limiting value defined by zone 3 in Fig. 2, the material loses its tensile strength in the direction parallel to $\sigma_2$.

(iii) **Crushing.** The crushing occurs when the state of stress is biaxial compression-compression and the stress level is beyond the simplified von Mises failure surface, shown as zone 4 in Fig. 2. Under this condition, the material also loses its strength completely.

THE FINITE ELEMENT PROGRAM (NLARCH)

The detailed description of the nonlinear finite element program (NLARCH) may be found elsewhere (Yang 1991). The general description of an arch and the analysis steps are illustrated in Figs. 3 and 4 respectively.

The fill between the two spandrel walls (see Fig. 3) is generally stone or brick debris. It serves mainly two purposes: firstly, its weight would provide further stability to the arch, thereby enabling a larger live load to be carried; secondly, it distributes the live loads applied at the road level down on to the arch rib. To incorporate actions of the spandrel fill, a masonry arch bridge may be simulated using two separated finite element analysis models (Yang and Loo 1991). Step 1 analyses the fill effect and load dispersion effect using a linear-elastic finite element model whereas Step 2 (see Fig. 4) analyses the structural behaviour of the arch rib using a non-linear finite element model. The finite element models for both the spandrel fill and the arch rib are presented in Fig. 5.
Zone 1

Zone 3

Zone 2

Zone 4

Fig. 2 - Cracking and crushing failure surfaces for masonry

Fig. 3 - Components of a masonry arch bridge

f'_t - tensile strength
f'_c - compressive strength

von Mises yield envelope
(Failure criterion:
\[ \sqrt{\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2 - f'_c} = 0 \])
Fig. 4 - Analysis steps.
In this study only circular arches are analysed because the shape is most common among masonry arches. To study the influence of the rise/span ratio, the rise $f$ as defined in Fig. 6 is varied whereas the thickness of the rib and the span remain constant. The results are plotted in Fig. 7. The value $f$ is varied from zero (a beam) to 2.0 (a semicircular arch) for the purpose of comparison. The failure patterns for the various values of $f$ are given in Fig. 8. It can be seen that a failure mechanism by forming three plastic hinges only occurs in the cases of beam ($f=0$) and semicircular arch ($f=2$) subjected to crown-point loading. The so-called plastic hinges are
identified by the circular dots in Figs. 8 and 9. The span and thickness used for this study (see Fig 6) are the same as those used in an experimental model tested by Towler (Towler 1981).

Fig. 6 The Model for a study of the effect of rise $f$.

Fig. 7 Effects of rise $f$ on the ultimate load.

The ultimate load for the symmetrical case reaches a maximum value when $f$ is 0.8m (0.8/4=0.2) whereas for a quarter-point loading condition, $f=0.6m$ (0.6/4=0.15) provides a maximum ultimate load. If the rise of an arch is too small (a shallow arch) or the rise is too big (a high rise arch), it would be disadvantageous to the strength of an arch. The rise/span ratios between 0.18 to 0.22 led to the maximum strength of the arch. This is generally applied to circular shaped arches. The adoption of the span/rise ratio for an arch may be restricted by the boundary conditions. Different ratio produce different horizontal thrusts at the supports which must be restricted. This may mean the particular shape is inappropriate.
Legend: o - Cracks

Fig. 7 Failure patterns of an arch by varying span/rise ratio (crown-point load).
Legend: o - Cracks

Fig. 8 Failure patterns of an arch by varying span/rise ratio (quarter-point load).
CONCLUSION

This paper has demonstrated the analysis of masonry arch bridges using a specially written finite element package. A parametric study of the geometry of arch has been presented and the changes in behaviour discussed. The maximum strength of the arch is achieved for span to rise ratios between 0.18 and 0.22.

The understanding of the behaviour and the method will enable more rational and unformed decisions when masonry arch bridges are evaluated and repaired.

REFERENCES


