Limit State Behaviour of Brickwork Arches

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Summary

This paper compares experimental results obtained from tests carried out on two brickwork arches constructed in the laboratory, with theoretical results obtained from a non-linear finite element analysis developed by the authors. Stress/strain properties of brickwork were obtained from axial loading of several brickwork piers of the same material tested in a constant strain machine. It was found that the collapse loads predicted by the analysis compared well with the theoretical results. The theoretical displacements based on the stress/strain law obtained from the brickwork piers were found to be overstiff when compared with the experimental displacements.

Introduction

Ever since the Roman times, brickwork and masonry arches have been an accepted means for bridging obstacles such as canals, rivers and roads. The age of many of these structures which have survived for hundreds of years bears testimony to their strength and durability. They are frequently required to carry loads far in excess of those originally envisaged, and engineers now face the task of assessing their structural adequacy for the task in hand. Occasionally, existing arch bridges are replaced by new arch structures. A need has therefore arisen to develop a rational method of analysis for existing and new bridges. This has been described elsewhere (1) and the object of this paper is to present experimental data confirming the validity of the authors approach.

Review of Methods of Analysis

All engineers are familiar with the 'middle third rule' which states that the line of thrust in an arch should remain within the middle third of the radial thickness of the arch rib. The conservative nature of this method has been discussed by Chettoe and Henderson[2] and Sawko and Towler[1]. Another approach used is the plastic analysis as proposed by Heyman[3]. This assumes that the line of thrust becomes tangential to the intrados or extrados at a sufficient number of sections to reduce an indeterminant structure into a mechanism. Sawko and Towler[4] illustrate that this method may be slightly unsafe but this is hidden by a geometric factor of safety of 2 which is applied to the minimum radial thickness. A geometric factor of safety of two has been found to be equivalent to increasing the applied load by a factor of 3 to 4. This method gives no indication about the degradation in the material stiffness and corresponding displacements and the extent of cracking.

A new analysis by Sawko and Towler[1] based on the finite element method has been developed because of the limitations of existing methods. It uses a two noded curve beam element with three degrees of freedom at each node. The analysis uses the parabolic stress/strain law proposed by Powell and Hodgkinson[5] to model the reduction in stiffness due to increased compressive stresses. It is known that brickwork can only tolerate a limiting tensile stress before cracking occurs. (This is generally assumed to be zero, but the model can incorporate a tensile contribution if required). This cracking produces a subsequent reduction in the flexural stiffness of the structure.

The loading is applied incrementally and a modified Newton Raphson method is used to ensure the structure is in a state of stable equilibrium with the applied loads. This load is applied until a convergent solution between the internal and applied load is no longer possible, at which stage the arch has failed.

Testing Procedure

Two brickwork arches were constructed in the laboratory at the Department of Civil Engineering, Liverpool University. Their dimensions are given in Table 1.

Arch	Span (m)	Rise (m)	Width (m)	Radial Thickness (m)
1	4.0	1.0	1.1	0.215 2 rings of brickwork
2	4.0	1.0	1.1	0.335 3 rings of brickwork

Table 1 Dimension of Experimental Arches

The main object of the tests was to validate the numerical method developed by the authors.

The arches sprang from two abutments, which provided a suitable inclined surface which allowed the bricks to be easily mated up to the concrete blocks. These concrete blocks were cast against stiffened uprights mounted on steel plinths which were tied together using 150 x 25mm mild steel connecting bars capable of withstanding a total tensile force of 2000kN. This arrangement ensured that the abutments were restrained and any spreading was prevented. These end conditions were designed to develop horizontal, vertical forces and moments at the springings, thus simulating an encastré arch as modelled by the numerical method.

When constructing the arch, a single row of bricks was laid out dry with no mortar, to verify the joint width and mark off the position of each brick on the form work. This ensured that during construction the position of each brick was predetermined consequently alleviating any problems which otherwise may have occurred at the crown. The outer edges were then laid and the interior of the ring infilled with brickwork to complete the first arch ring. This procedure was repeated two or three times depending on the number of rings required.

The dead weight of the infill, which was to be applied to the arch, was simulated by using 20kg weights. These had to be seated on the arch ring and this was achieved by casting a number of independent concrete steps on the brickwork. When casting the steps care was taken to ensure that they were totally separate from each other so that there could be no interaction between them, preventing any transfer of stress through the concrete steps.

The live loading was simulated by a line load across the width of the arch. The source of the load was a high pressure hydraulic pump. The load was distributed across the arch by using a thick box section spreader beam which was positioned and bedded in mortar beneath the loading points.

The applied load was monitored by interposing a load cell between the pump and spreader beam. The vertical deflections were measured using dial gauges at every 500mm along the extrados of the arch. Gauges were mounted either side of the arch to check that the arch was deflecting uniformly across the width. The strain distribution through the arch rib was measured using a Demec gauge with four sets of Demec points positioned through the rib thickness at any particular section. These groups were located at sections which were expected to exhibit the most variation in strains, particularly at load points, in some instances they were used to monitor cracking. Figure 1 gives a schematic illustration of the arch and shows the positioning of instrumentation and loading.

Testing of Brickwork Piers and Arches

Tests were carried out on 8 course brickwork piers to determine the compressive characteristics of the brickwork used in the arches. The bricks used were a 5 hole perforated, extruded brick with a characteristic strength of 65N/mm^2. The mortar was 1:¼:4 mix with a compressive strength of 10N/mm^2. The tests were carried out using an incremental strain to determine the amount of strain softening in the brickwork. These tests were carried out by the British Ceramic Research Association (B.C.R.A.) and the stress/strain curves produced are remarkably similar to the parabolic stress/strain law suggested by Powell and Hodgkinson[5]. The results obtained have been given in Figure 2 and it can be seen that by using a maximum compressive stress, σ_m = 16N/mm^2 and a corresponding compressive strain $\varepsilon_m = 0.0034$ in conjunction with equation (1) gives a very good approximation to the measured results.

$$\frac{\sigma}{\sigma_m} = \frac{2\varepsilon}{\varepsilon_m} - \frac{\varepsilon^2}{\varepsilon_m^2} \qquad (1)$$

Tests carried out on the arches included point loads at the quarter point and crown. Also tests were carried out using combined loads i.e. the crown and quarter point loads were applied simultaneously. These latter tests have been omitted for brevity. Serviceability tests were carried out using these live loads with two types of dead load which represented an infilled horizontal road surface of 0 or 250mm above the extrados at the crown.

Comparison of Experimental and Theoretical Results

Table 2 shows the loading used in these tests and compares the theoretical collapse loads with the measured experimental failure loads for cases 4 and 7. The serviceability load experienced during other cases have also been tabulated.

Load	Arch	Loading		Max. Load (kN)	
Case	Type	Dead	Live	Expt.	Theo.
1	1	0	QP	25.3	22
2	1	0	Crown	51.3	90
3	1	250	QP	22.1	36
4	1	250	Crown	82.5	100*
5	2	0	QP	42	68
6	2	0	Crown	120	980
7	2	250	QP	117	102*
8	2	250	Crown	140	980

Table 2 Comparison of Experimental and Theoretical Loads
* Collapse Load

From the results it can be seen that the comparison between the theoretical and experimental collapse load for the two and three ringed arch was +21% and -13% respectively.

Figure 3 illustrates the theoretical and experimental load/displacement curves for the two ring arch. Although great care was taken to ensure the arch displaced regularly across the width, some deviations occurred either side. For this reason the experimental results, plotted represent the mean value of the two sets of dial gauge readings either side of the arch. Two sets of theoretical curves have been plotted using an initial value of Young's modulus (E_D) of 9400N/mm^2 obtained from the 8 course piers and of E_D = 6000N/mm^2.

Figure 3 shows that the arch is more flexible than predicted by the numerical formulation, using a value of 9400N/mm^2 for Young's modulus obtained from the tested piers. Two reasons can be offered for this discrepancy. Firstly, material properties obtained from pier tests might not be directly applicable to rib behaviour because of the different method of bonding used. Secondly, the numerical formulation predicts an over-stiff behaviour of the arch rib. It is felt that the combination of these two factors were responsible for the discrepancy.

Fortuitously, deflections in brickwork arches are very small, and have a negligible influence on the collapse load obtained.

Conclusions

1. The collapse load predicted by the theoretical model agrees well with the test values. For the two arches tested, predicted values were +21% and -13%

of the test values for the two and three ring arches respectively. The method can be safely used for the analysis of existing and new arch bridges.

2. Brickwork arches are very rigid and exhibit small deflections under load.

3. The numerical model developed appears to over emphasise the stiffness of brickwork arches, when based on results obtained from uniaxial compression tests.

References

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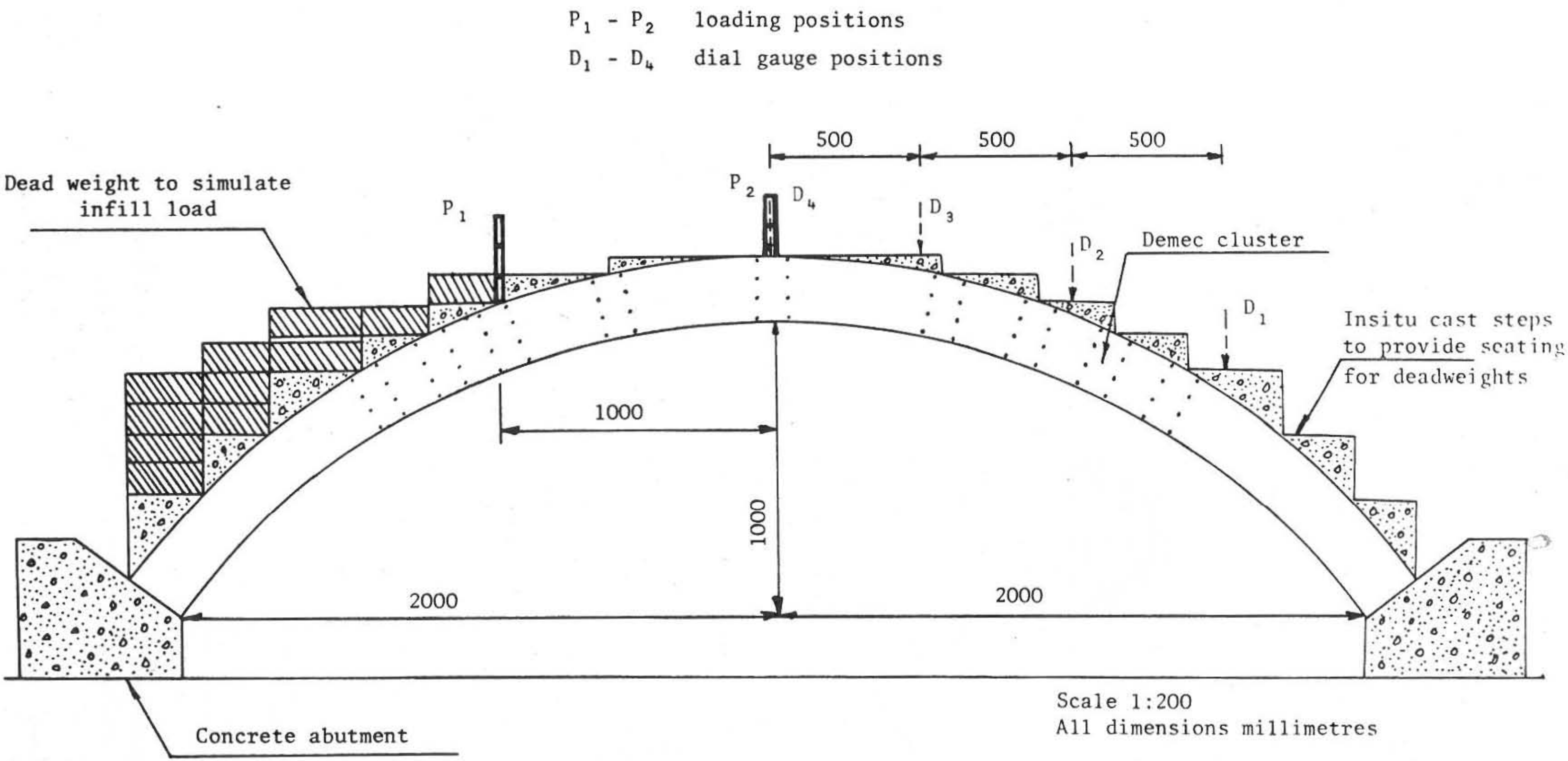

Figure 1 Diagram of Instrumentation and Loading Condition for Brickwork Arch

N.B. Deadweights and dial gauges are only shown on one side for clarity.

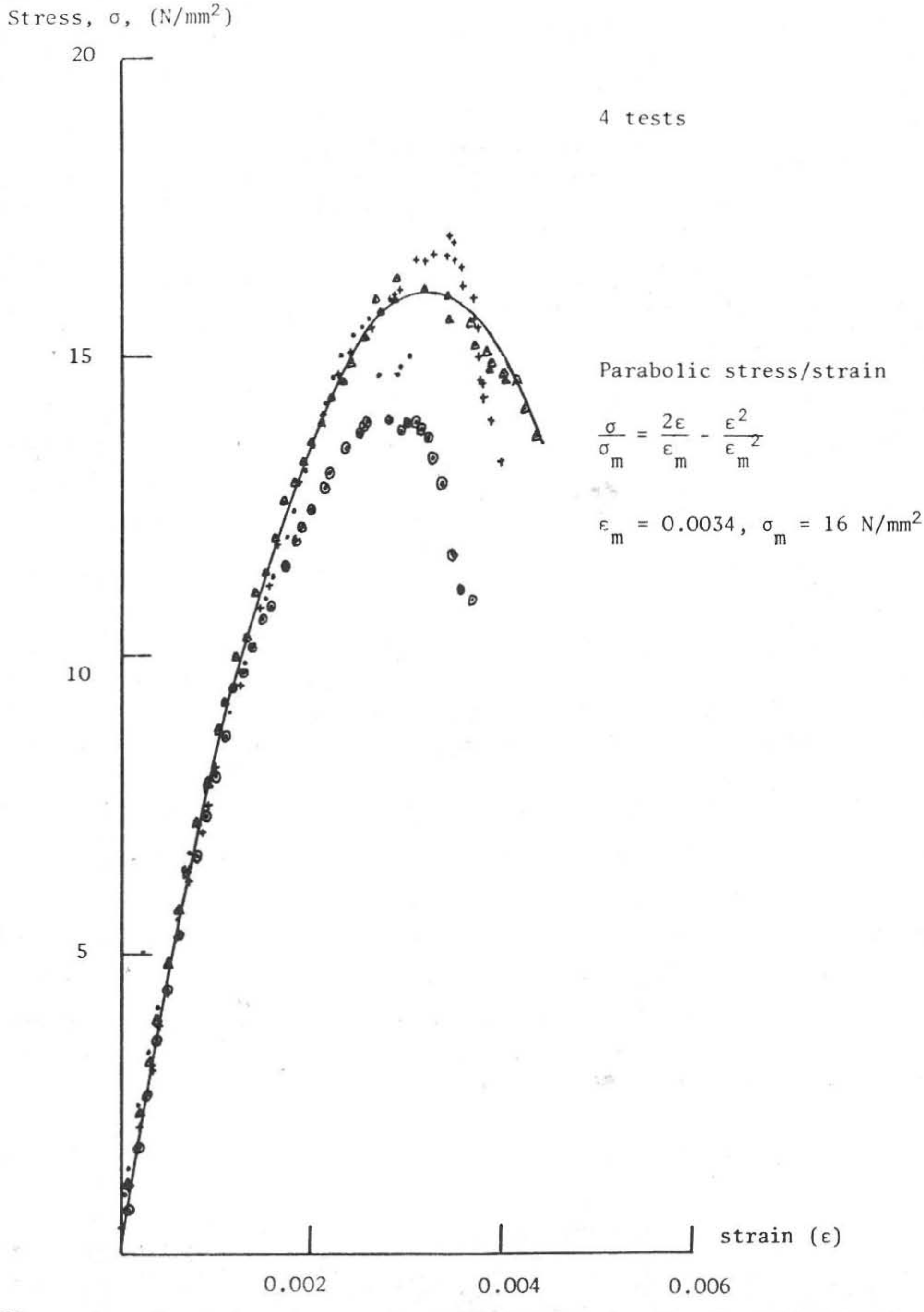

Figure 2 Comparison Between Experimental Results (performed by BCRA) and the Theoretical Parabolic Stress/Strain Law.

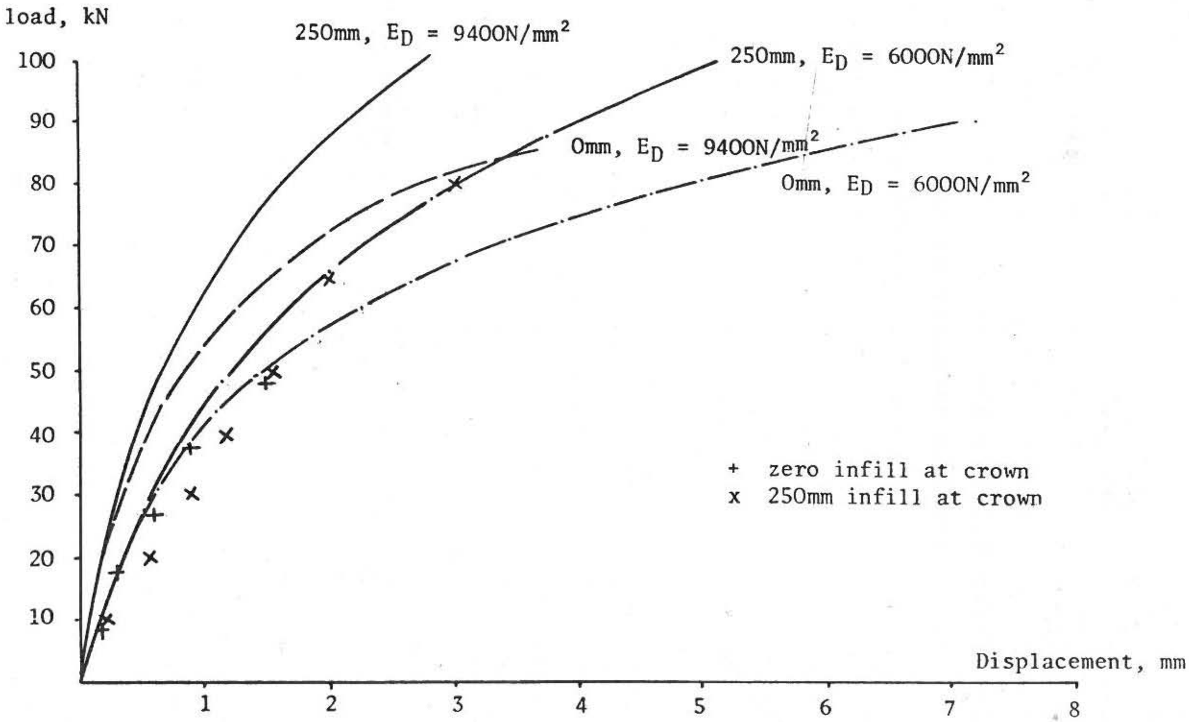

Figure 3 Comparison of theoretical and experimental load/displacement curves for a crown live load on a two ring arch.