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THREE DIMENSIONAL BEHAVIOUR OF MASONRY ARCH BRIDGES UNDER SERVICE LOAD

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Abstract

This paper presents the result of series of small-scale centrifuge model tests on 2-D and 3-D shallow and deep arches under service load. One-twelfth scale models of a 6-m single span arch bridge were accelerated in a centrifuge up to 12g to ensure that the prototype stresses were properly reproduced. Under this acceleration full arch width steel and lead rollers, equivalent in the prototype to a single 2.5m axles weighing 12 and 15 tonnes respectively, were passed over the bridge in alternate directions. To understand the behaviour of 3-D arches under unsymmetrical load one half of the lead roller was passed over the arch along different lanes. The deflection of the structure was recorded by three rows of displacement transducers beneath the structure. In addition the pressure at the interface between arch barrel and backfill was recorded using diaphragm pressure sensors flush bonded into bricks within the arch barrel.
The results of these tests clearly show the three-dimensional behaviour of the masonry arches. The soil pressures and deflections under the narrower rolling load show the out of plane bending of the barrel at the location of the load whereas the overall response on the side of the arch remote from the load is uniform. The comparison between the 2-D and 3-D behaviour demonstrates the affect of the spandrels in stiffening the arch barrel and in reducing the interface pressures in the fill. Also significant in both 2-D and 3-D behaviour is the effect of the load history on the measured pressures and deflected shape.

Key Words

Masonry, Arch bridges, Centrifuge modelling, 2-D & 3-D model.

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1 Introduction

Masonry arch bridges remain one of the most important elements in many countries transportation systems. Although significant research has been conducted in recent years to determine masonry arch behaviour at the ultimate load(Page 1993) limited work has been undertaken on their response under service load. In the USA the deflection of several arches under truck load was recently published(Boothby, Domalik et al. 1998). Behaviour of a 32 m stone arch bridge in Ireland under service load test has been modelled using finite element by Fanning (Fanning and Boothby 2001). In the UK a series of tests were undertaken on the, then, newly constructed Kimbolton Bridge to measure the fill stress under heavy axial load (Ponniah, Fairfield et al. 1997). The results of these tests again were also compared with FE analysis. Series of small scale two dimensional centrifuge models have also been constructed and tested under a range of different loading conditions (Baralos 2002; Burroughs 2002). The models were 1/12 scale model of single span arches with a 6-m span tested in a centrifuge at an acceleration of 12g. This type of model has been used at Cardiff University to successfully simulate the behaviour of ultimate state behaviour and soil/masonry interaction.

The objective of the present study is to try to experimentally quantify the differences between the behaviour of two dimensional and three dimensional arches under service load conditions. The principle difference between the two models is the inclusion of the spandrel walls in the 3-D model. The spandrel walls are however not extended to form parapet walls. Most current UK assessment methods do not consider the strengthening effects of the spandrel or parapet walls because their contribution at ultimate load is suspect. However their contribution under service loading is more assured and therefore quantification of their effect represents a significant goal.

2 Geometry and experimental procedure

2.1 Arch geometry and materials

The arch models were made from brickwork formed from scaled bricks. The bricks were 1/12 full size scale in width and 1/6 full scale size in length and depth. The model bricks were cut from full scale bricks using precision indexed saws. The arch barrel was made of three rings of bricks with a UK mortar joint type v with a mix content of 1:3:12 (Cement: Lime: Sand) by volume. This technique has been used and established in previous works (Baralos 2002; Burroughs 2002). The same bricks but with a different size were used to build the spandrel walls. The 2-D and 3-D arches were built with essentially the same geometry, masonry, mortar and fills. Details of models and tests are given in Table 1.

The deflections of the arches were measured via rows of Linear Variable Displacement Transducers (LVDT) located at 2%, 15%, 25%, 35%, 50%, 65%, 75%, 85% and 98% of the span. For the 2-D arches two rows equidistant from the centreline were used for the 3-D tests the three rows were located along the centreline and close to the front face and back face of the arches. In addition vertical movements on the top of the spandrel walls were similarly measured. Readings were recorded at 6 second intervals throughout both the service and ultimate load tests. Details of the service loads are also contained in Table 1. The soil/masonry normal pressures were measured by small diaphragm pressure transducers (manufactured by Kyowa) which were preinstalled in bricks and then laid within the brickwork with the other brick units. Pairs of these pressure gauges were placed across the arch usually at 7%, 15%, 65%, 75% and 85% of the arch span. A general view of arch model is presented in Figure 1.

Table 1 Detail of models under test

Parameter	Dimension
Intrados span (mm)	500
Span to rise ratio (Shallow arch S2D- B)	4
Span to rise ratio (Deep arch D2D- B)	2
Fill depth at crown (mm)	30
Arch ring thickness (mm)	30
2-D width (mm)	345
3-D width (mm)	405
Spandrel wall thickness (mm)	30
Mortar mix(cement: lime: sand)	1:3:12
Whole brick compressive strength (N/mm2)	96
Fill bulk density (kN/m3)	20.5
ϕ’(Angle of friction)	53

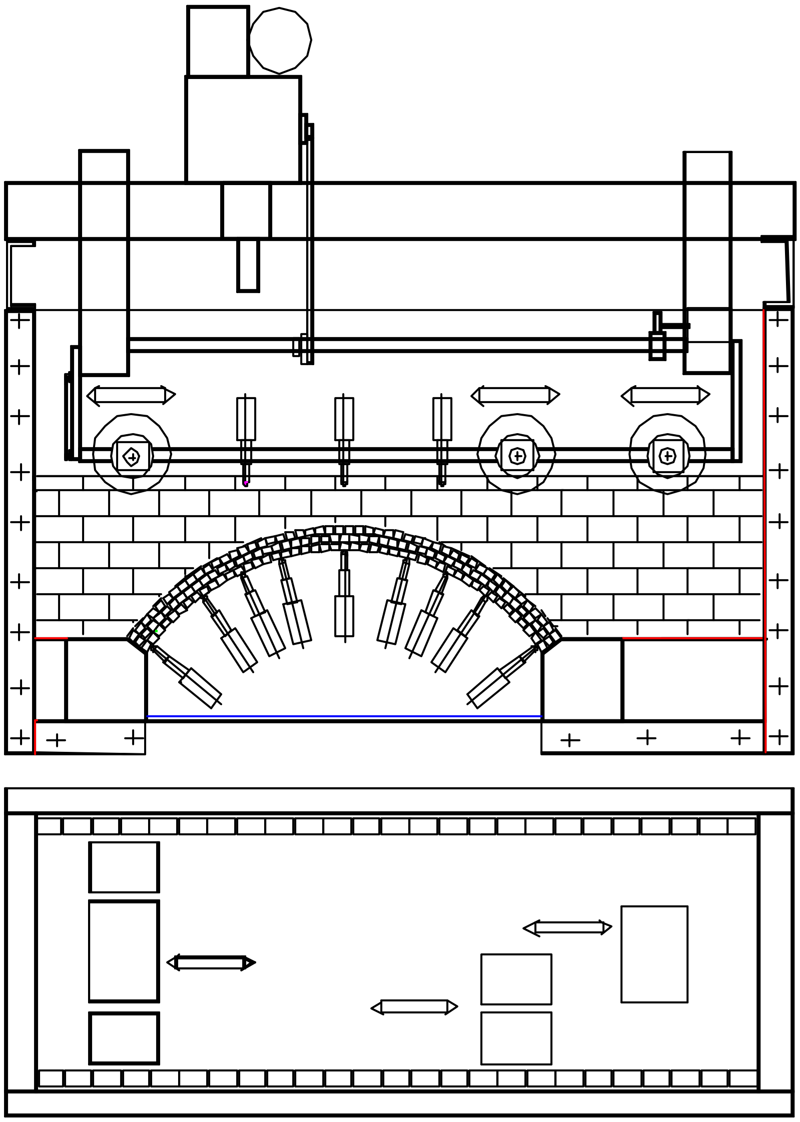

Figure 1 Model package and roller details

2.2 Service Load and measurements

Service loads were applied to each arch using, usually, three in-line hollow metal rollers (annuli). A push system supported remotely from the test specimen was used to move the rollers during the test. The push bar was attached to two threaded metal roads, which both rotate at a fixed speed during any test, the pair ensures push bar and thus the rollers remain perpendicular to the axis of the arch. A large range of gearing is available through the drive system but the rollers are set so that a single traverse of the arch bridge takes approximately 20 minutes. The loading can therefore be seen to be quasi static but does move forward smoothly and is therefore much preferable to the sequential adjacent patch loading always used in full scale model simulations of service conditions. The rollers were constructed of lead, steel and aluminium which are equivalent to 15, 12 and 7.5 tonnes in the prototype. The outside diameter of the rollers is approximately 75mm. Fourteen passes of the roller were usually applied in the first stage of each test. Details of the rollers used and pass number in each test are presented in Table 2.

3 Test results

3.1 2-D Test results

3.1.1 2-D Arch deflection

The 2-D arches were built without spandrel walls and acetate sheets were placed between the fill and side walls of the rigid support box, within which the models were built and tested in the centrifuge. Figure 2 details the deflection of the arches when the rollers are located on the crown of the arch at pass 14 and the direction of the roller movements are from the left to right abutment and the loads are as given in Table 2.

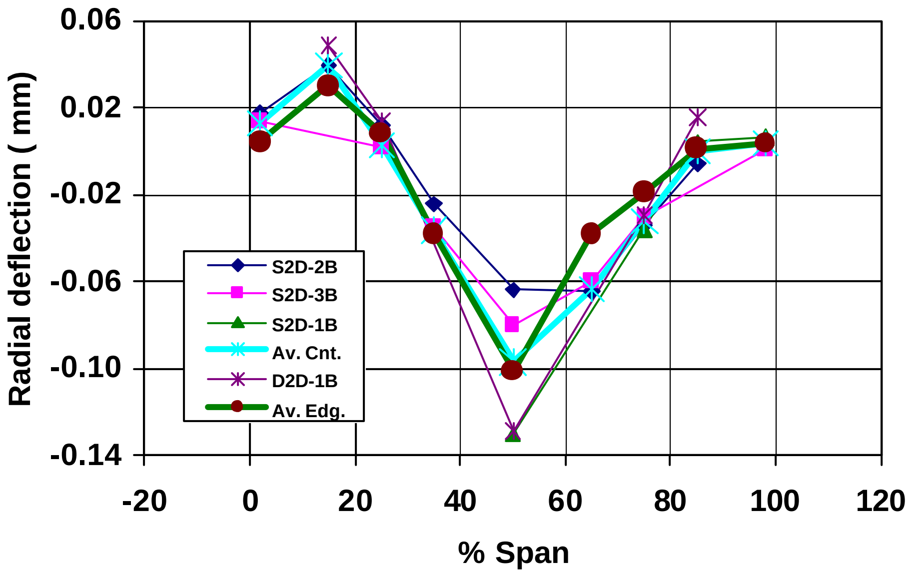

Figure 2 2-D arch deflection under load at 50% span

The figure is typical of the average behaviour of the arch at the centre line and front (and back) face. Figure 2 shows an excellent agreement between the arch deflection at centre and at the front of arch under symmetrical service load. This confirms the two dimensional behaviour of model under these rolling load. The same result was recorded when the roller was located at the other positions along the arch span.

Table 2 Detail of service load

Test ID	Rolling type
S2D-1	14 pass Steel roller
S2D-2	14 pass Steel roller
S2D-3	14 pass Steel roller
S3D-1	18 pass Steel roller
S3D-2	14 pass Steel roller , 6 pass lead roller type 1 and 2
S2D-3	14 pass Lead roller , 6 pass lead roller type 1 and 2

1 half of lead roller applied on the centre of arch
2 half of lead roller applied on front face of the arch

3.1.2 2-D Soil/Masonry interaction

Figure 3 shows the soil/masonry interface pressures on the arch barrel measured using the small pressure transducers. The figure shows, as expected, that the maximum pressure occurring during the test was achieved when the roller was directly above the pressure cells. The results also indicate (not shown) that the pressures decrease with increasing the pass number of roller. This all confirms results previously presented by other researchers (Burroughs, P.O. et all 2000).

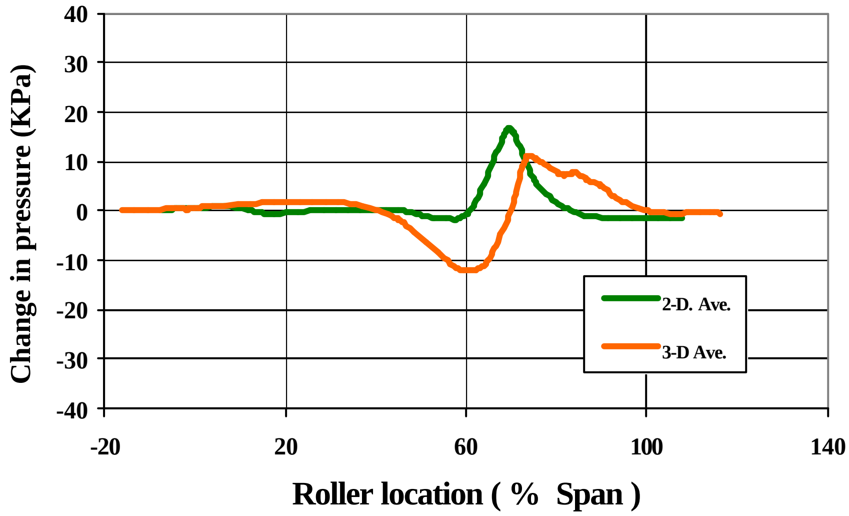

Figure 3 Soil arch interface pressure at 75% of arch span

3.2 3-D Test results

3.2.1 3-D arch deflection under symmetrical loads

The deflections of the arches at 50% of the span are shown in figure 4. There is good agreement with the results from different tests. The averages of the arch deflections at the same section from the 2-D and 3-D tests are presented in this figure. Comparison of the average data from the 2-D and the 3-D tests shows less defection of arch barrel in the 3-D tests. A similar result was recorded in the other LVDTs beneath of arch barrel during the service load test.

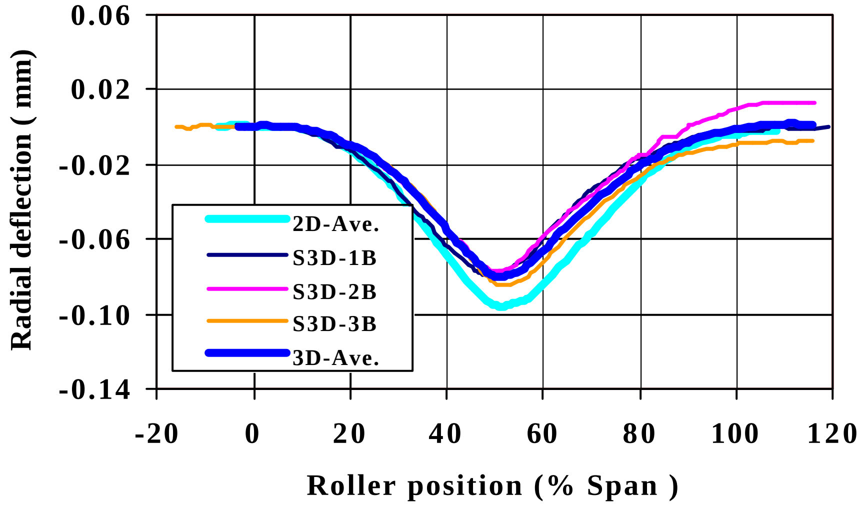

Figure 4 Deflection of arch at mid section under service load

In Figure 5 the deflections of arch at 75% of the span in the 2-D and 3-D arches are compared. Again the deflections of the 3-D arches are less than the 2-D models but there is no significant difference between the recorded data under the centre line and the front edge of arch.

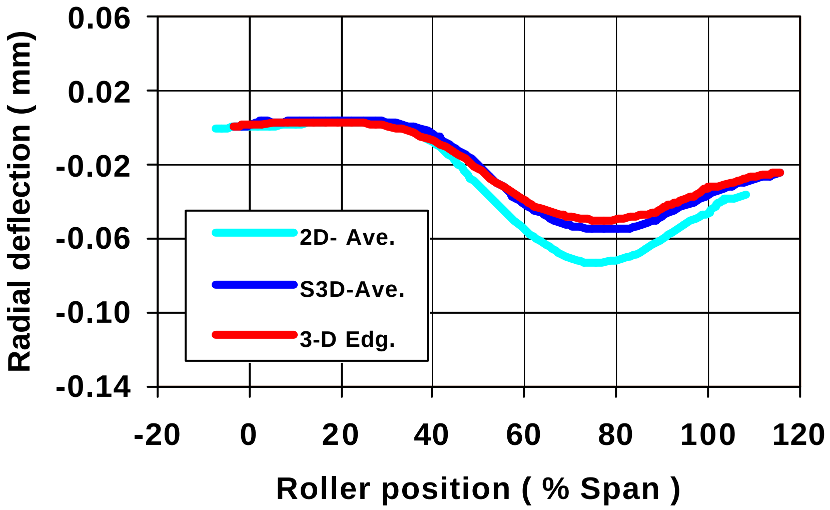

Figure 5 Comparison between 2-D and 3-D arch deflection at 75% span

3.2.2 3-D arch deflection under unsymmetrical load

In the 3-D models after the first part of the service load test, the equivalent full width rollers were replaced by a single roller one half the weight of lead roller (equal to 7.5 tonnes in prototype). This roller was applied on central line of arch and after 6 passes the test the centrifuge was stopped. In the next stage two rollers equivalent to the single roller (as shown in Figure 2) were applied to the front half side of arch and model was retest. These tests represent both symmetric and un-symmetric 3-D tests.

Figure 6 shows the arch deflection recorded along the centreline row of LVDTs when the load was located at 75% of the span for different roller types. The data from this part of the tests shows the 3-D behaviour of arch and also the out of plane bending of the arch very clearly.

The result indicate that the maximum deflection of the arch under half of the load is approximately half of the measured deflection at the same section under the full roller load, this confirms the “elastic” behaviour of structure at this load level. The deflection of arch recorded along the 3 different sets of LVDTs is detailed at Figure 7 when the

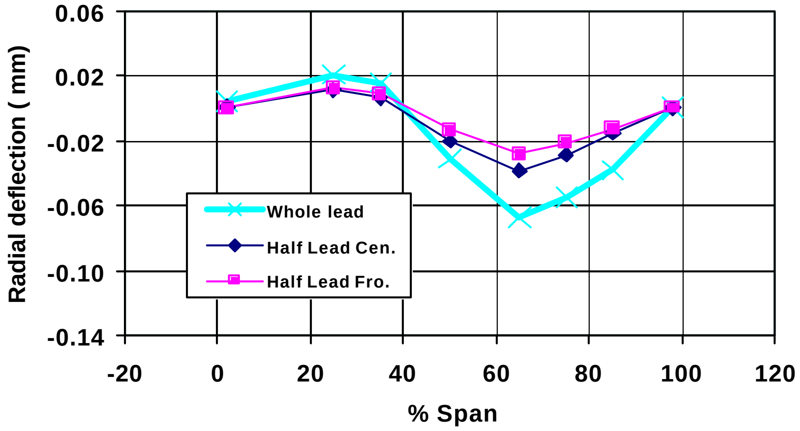

Figure 6 3-D arch deflections under different rollers

load is applied to the front of arch. The maximum deflection was recorded by front the LVDT and minimum of the deflection is measured by far LVDTs. It is clear form Figure 7 that there is a significant 3-D effect caused by off line loading. The arch does not appear to laterally distribute the load perhaps as much as previously considered

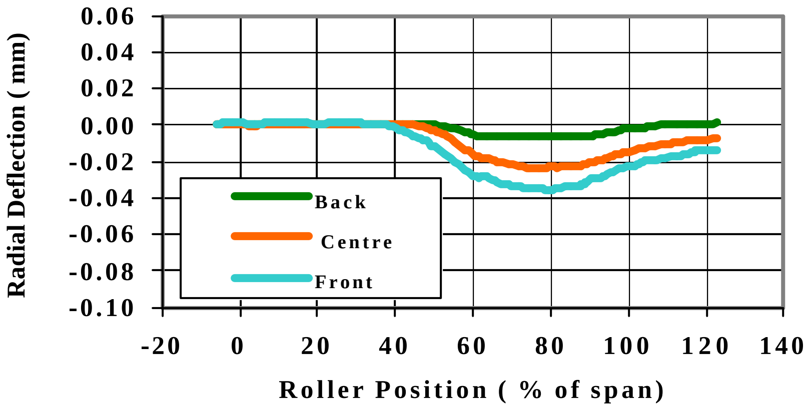

Figure 7 Arch deflections at 75% span for different load positions under front edge roller

4 Conclusions

- Out of plane bending was apparent even at low levels of service bad. The quantification of this effect is not yet complete.
- The spandrel walls appear to attract some of the load away from the soil/arch interface reducing both the vertical pressures under the load and the soil pressures caused by the sway of the arch.
- The Spandrel walls have decreased the deflection of the arch under service load although this is perhaps not as significant as might previously be considered. In this regard the importance of the fill as an “equivalent” to the spandrel walls should be considered especially for old masonry where the quality of the

spandrels may have reduced through natural deterioration whereas the quality of the fill may have improved through consolidation and compaction.

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