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System Behaviour in Masonry Arch Bridges

Comportement des ponts à arc en pierre

Über das Tragverhalten gemauerter Bogenbrücken

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SUMMARY

The paper discusses the various interactions which are present in masonry arch road bridges. These occur between the wheel and the pavement, the pavement and the soil fill, distribution in the fill itself, interaction between the fill and the arch producing active, at-rest and live load pressures at different points, load distribution within the arch barrel itself, interaction between the arch barrel and the spandrel walls and between the complete structure and its foundations.

RÉSUMÉ

L'article examine les interactions diverses qui caractérisent les ponts routiers à arc réalisés en pierre. Celles-ci se produisent entre la roue et le revêtement de la chaussée; entre la chaussée et le remblayage; dans le remblai lui-même; il y a aussi l'interaction entre le remblai et l'arche produisant des pressions de poids actifs, statiques et dynamiques à des points différents, la distribution de la masse avec le berceau de la voûte, l'interaction entre le berceau de la voûte et le tympan du pont et entre la structure entière et ses fondations.

ZUSAMMENFASSUNG

Der Beitrag behandelt die verschiedenen Interaktionen, die in Bogenbrücken auftreten. Interaktionen finden zwischen den Radlasten und dem Fahrbahnbelag, zwischen dem Fahrbahnbelag und der Erdaufschüttung, der Aufschüttung und dem Tonnengewölbe, dem Gewölbe und den Seitenwänden, dem System von Gewölbe und Seitenwänden und den Widerlagern und zwischen Widerlagern und Fundament statt. Die Lastverteilung in der Aufschüttung ist ebenfalls von Bedeutung, da sie die Lastverteilung auf das Tonnengewölbe bestimmt.

1. INTRODUCTION

The structural behaviour of arches has been a matter of concern to scientists and engineers ever since the blossoming of science in the Renaissance. The development through Hooke's line of thrust and Couplet's mechanism analysis to Castigliano's elastic analysis of arch rings, described so thoroughly by Heyman[1], has concentrated the minds of engineers on the arch itself, whereas in most structures the arch is merely a small part of the whole. The two-dimensional view is particularly inappropriate to arch bridges; nonetheless, it still holds sway. Arch bridges are such complex structures and yet such cheap ones that the huge expense of a three-dimensional analysis, though it is now possible, is rarely, if ever, economic.

The objective of this paper is to set out the various elements of the structural system of an arch bridge, the way they interact and how we might put quantitative boundaries on the interactions which we either cannot, or cannot afford, to explore thoroughly.

2. THE TWO-DIMENSIONAL SYSTEM IN ARCHES

Arches are statically indeterminate, particularly so since the interaction between the foundations and the arch have a rather greater effect on structural behaviour than do the same interactions in more modern structures. If an arch rib were a perfect fit between its foundations in the dead load state, it would behave elastically under modest live loads. If we analyse the arch elastically, we neglect a major part of its behaviour. To emphasise this quantitatively, a typical 10 metre span semi-circular masonry arch, treated as if it were an elastic medium and subject to 3mm spread of the abutment, looses all its net thrust at the crown and behaves exactly like an elastic beam. Because this is both a quantitative and a qualitative change in behaviour, it shows clearly why we can never determine, or even make a reasonable approximation to the actual state of stress, in a working arch bridge.

Soil:structure interaction is a matter of increasing interest to engineers. This is normally viewed in the light of the response of a structure to foundation movement and the response of the foundations to stress in the structure. In arch bridges, these effects are compounded by the fact that most bridges have soil fill above the arch to make the road up to formation level. The result of this is that as the arch flexes under load, the pressure applied to it by the soil varies. Measurements on large scale model bridges have shown that a patch load applied at the road surface is distributed through the fill and appears on the back of the arch as a somewhat more distributed pressure patch. Surrounding this patch, the arch is pushed away from the soil and the pressure is slightly reduced. On the far side of the span, the arch moves into the fill and this causes a passive response from the fill which helps to stabilise the arch. Figure 1 shows an arch subjected to load in this way, with the corresponding pressures, ring stresses and deformation. It should be noted here that the deformation pattern will be the same regardless of

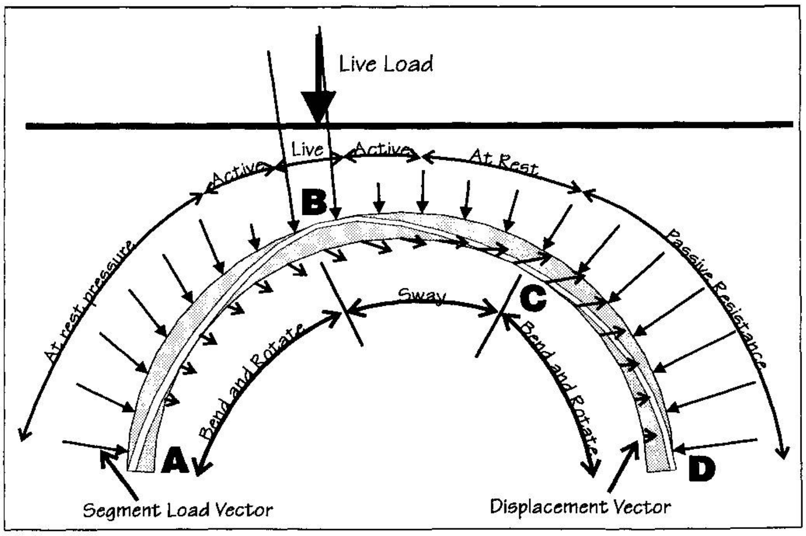

Figure 1 Arch movement and corresponding soil pressures under load

the material from which the arch is built. Even a steel ring would be pushed down at the load point and would rise into the fill at the opposite side. The fact that a masonry ring cannot carry tension reduces the stiffness in places and therefore increases the curvature.

2.1 Initial stress effects and abutment movement

Given that the thrust in an elastic 10 metre span arch can disappear with only 3mm of movement at the abutments, we must acknowledge that no real abutment can be regarded as sensibly rigid. The behaviour of the arch ring must therefore be modified by the fact that it stands on non-rigid foundations. When the centring is removed from an arch, the load is transferred from a temporary support into thrust in the arch ring and a reaction from the abutments. As a result, the ring must shorten and bend, and the abutments must move apart as well as downwards. The net effect of this, as described elsewhere[2], is to force the thrust upwards at the crown and downwards at the springings so that even before any live load is applied, the bending stiffness of the arch is likely to be reduced at these points; that is to say there will be some loss of section at the crown and the springings.

As a live load is applied, the effect is to shift the thrust and therefore the low stiffness zones as shown in Figure 2. Only as the live load approaches the ultimate value for the system described will stiffness reduce dramatically in the opposite sense at the springing remote from the load so that the arch ring tries to form a mechanism and is only held in place by the fill. At this stage, arch ring deformation may become gross and something approaching the full passive pressure may be mobilised from the soil fill before final failure of the system. It should be noted, however, that gross deformation which is required to develop passive pressure modifies the geometry of the arch, reducing the effective rise and increasing the thrust. The law of diminishing returns comes into action rapidly, so that a load deflection curve for the arch would be well into the falling branch before passive pressure is fully realised.

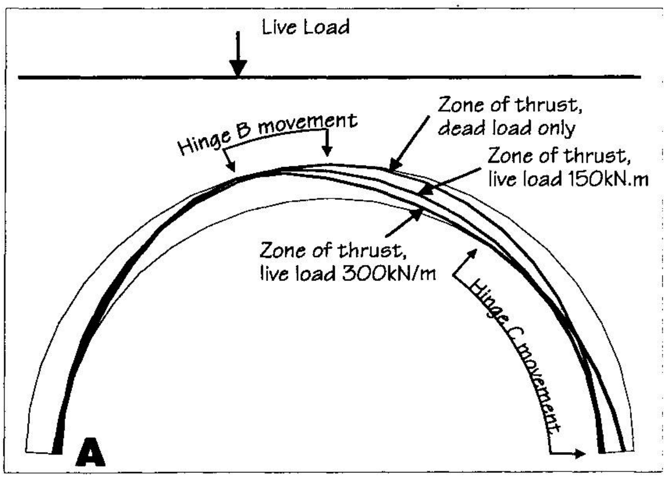

Figure 2 Movement of "hinges" as load is applied

2.2 Three dimensional effects

Models have been constructed at moderate scale with an arch ring which truly represent this two-dimensional behaviour, and all the effects described above could be observed and, indeed, measured. A three-dimensional model was constructed with spandrel walls but otherwise identical to one of these 2-D ones and the behaviour observed was substantially different. As before, where the patch load was applied, the resultant appeared as a patch load on the upper surface of the arch but the patch was much less distributed than in the previous case. The reason for this change has not yet been tested but it would seem likely to relate to an increased stiffness of the arch ring caused by the presence of spandrel walls.

The smaller patch of pressure on the back of the arch caused by the live load was surrounded by an area of reduced pressure where the arch deformed away from the fill. What was perhaps more surprising was that the passive pressure induced at the opposite side of the arch was reduced. It is thus clear that although there was negligible transverse distribution of load through the fill, the structure was managing to produce a distribution. Masonry is assumed to have no tensile strength. This is obviously something of a simplification since, in one direction at least, interlocking of the masonry units will mean the strength is rather more than that which can be mobilised in the bond between the units and the mortar. Nonetheless, it is reasonable to assume that the transverse bending stiffness of the arch is small.

How then can the structure provide lateral distribution. To understand this it is necessary to look first at the motion vectors of various parts of the arch shown in Figure 1. When this is done, it becomes clear that a major component of the deformation is in the form of sway and is much less characteristically normal to the surface of the arch than might at first appear. In order for transverse distribution not to take place it would therefore be necessary for shear deformation to take place within the membrane of the arch itself, and we would expect the arch to exhibit enormous stiffness against such deformation. The critical area in this respect is that between points B and C in the arch (Figure 1).

A look at the aspect ratio of this element of the arch will give a picture of what sort of distribution might be achieved. A typical wide bridge might carry four lanes of 3 metres on a span of 15 metres. This central swaying zone of the arch would then have an aspect ratio roughly 5 metres deep by 12 metres wide. If the spandrel walls were to provide support over roughly a metre at each edge, this section of the arch would become, in plane, an extremely deep beam, the behaviour of which would be governed by shear deformation, even if it had substantial tensile strength. Most arch bridges are 8 metres wide or less, so that the aspect ratio of the swaying section is likely to be at least 2:1 in any real bridge. This implies that sway mode edge stiffness provided by the spandrel walls will be sufficient to ensure that negligible sway actually takes place. All the passive action required to stabilise the arch comes from the walls rather than the fill. This implication is borne out by the practical measurements which have been made.

3. LOAD PATHS IN ARCH BRIDGES

Having described the stiffening mechanisms of the arch, it becomes possible to trace the load path through the structure in terms of lines of thrust. A vertical patch load applied at the load surface must be supported by a vertical reaction vertically below it from the arch barrel. The live load thrust in the arch must therefore be concentrated in a relatively small area underneath the load. From here the thrust will fan out towards both abutments, the degree of fanning will depend on the in-plane stiffness of the arch barrel and the stiffness of the structural elements and foundations supporting it.

The spandrel walls will be stiff in the plane of the arch. Whatever foundations they have as they extend back behind the abutment wall, the spandrels will have noticeably larger foundations than a similar width of abutment. Thus the spandrels must be substantially stiffer than those parts of the structure supporting the rest of the arch width.

Provided the arch does not crack at the inside face of the spandrels, it is reasonable to model the spandrels as adding a horizontal component of force to the arch thrust at point C, and similarly attracting a substantial proportion of the thrust at the springing of arch closest to the application of load, A. The potential for producing this horizontal component can be checked by considering the possibility of horizontal shear failure longitudinally in the wall. It is, however, quite unlikely that such a failure would take place in a real bridge.

4. MODELLING FOR ANALYSIS, ASSESSMENT AND DESIGN

Modelling this complex three-dimensional behaviour in such a way as to assess failure criteria remains extremely difficult. Computer software to simplify such analyses is under development in Dundee, but in the meantime we must consider whether such refinement is truly necessary, rather than just desirable.

We have seen that if an arch is built as a two-dimensional structure with no edge stiffening, it behaves in the anticipated way, generating active and passive soil pressures at appropriate points around the arch ring. If, as sometimes happens, the arch were to crack in line with the inside face of the spandrels, much of the interaction with the spandrels would break down. A detailed discussion of these possibilities is presented in reference [3].

It might be necessary, for practical purposes, to take account of only the two-dimensional structure and such lateral load distribution as the arch may be able to produce within the width of the structure. It is therefore proposed that for assessment and design purposes the arch should be analysed on a width equal to the distance between the inside face of the spandrels which may be reasonably taken as 1m inside the overall width at both faces. Such traffic load as can be applied between these boundaries should then be assumed to be distributed across that whole width. It should be noted that in many bridges it will not be possible to load more than one vehicle in this effective width. If two vehicles pass on the bridge, one wheel of each may well be positioned over a spandrel wall (Figure 3). The analyst should recognise that the effect of the wheel loads is not distributed uniformly across the full width of the arch at the point of application as is implied by this assumption. It should equally be recognised that the structure will have additional capacity as a result of the alternative load paths which are available to it, including friction between the soil fill and the spandrels. Therefore the assumptions are conservative.

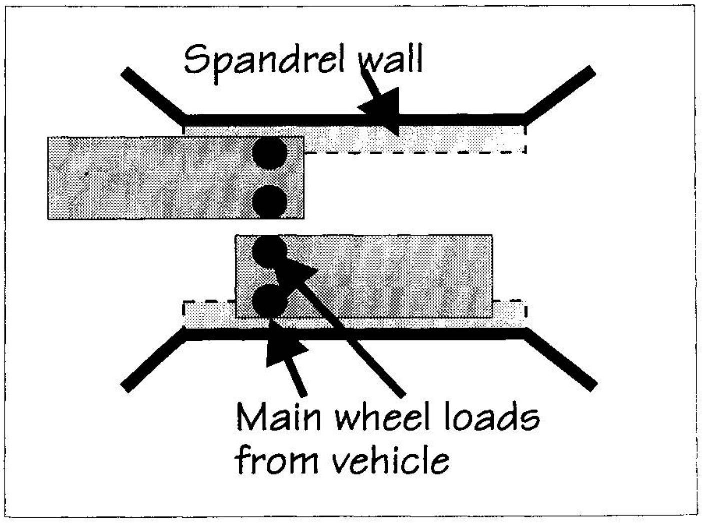

Figure 3 Vehicle loads on a typical arch bridge

5. CONCLUSIONS

1 Masonry arch bridges are complex three-dimension structures.

2 The gross difference in stiffness of various elements of the structure substantially affect its load distribution characteristics.

3 It is reasonable to assume that any point load applied is distributed across the full width of the arch. Such distribution will not be as a result of transverse bending but of tangential shear, and will take place at an angle of at least 45° to the direction of span.

4. If a detailed analysis is required, the supporting action of the spandrels can be assessed in terms of longitudinal sliding shear resistance.

5 Much further work is required before a complete three-dimensional analysis of the structure is possible.

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