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Semicircular arches

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For some time now, our Company has been taking the lateral effects of fill into account in the assessment of masonry arch bridges, and it is surprising to learn that the Authors regard it as a new concept. The results of some of our work on the effects of lateral pressure are presented briefly in reference 12. These results demonstrate the effects of varying fill parameters and show that the calculated load-carrying capacity of an arch is considerably increased when lateral pressure is taken into account. However, care must be taken to use realistic fill parameters, because material used as fill over arches tends to be of dubious quality. The Authors are correct to point out that the Rankine approach has limitations and we await with interest the results of their investigations. It must be borne in mind, however, that lateral pressure is only one of a number of factors that show arches to be stronger than can be predicted by strict adherence to the classical methods of Pippard and others.

17. We agree with the Authors that the problem lends itself to computer analysis. We have been using in-house routines for arch analysis for some time now, and have recently been persuaded to refine these, and to market them as a commercial masonry arch analysis program.

18. This program has shown that when factors such as effective load dispersion, effects of lateral pressure, effects of haunching materials, effects of multiple axles and variations in longitudinal road profile are taken into account, then the positions of the postulated hinges are uncertain. We advocate, therefore, that the computer program should automatically investigate all permutations and combinations of hinges in order to bring what is essentially an upper bound solution as near as possible to the lower bound. Such a program leaves the assessment engineer free to vary the other parameters in order to obtain a feel for the sensitivity of the structure to the effects of these parameters; thus a more realistic engineering judgement as to the capacity of the structure may be made.

19. We have found that even when all possible hinge positions have been investigated, the mechanism method can still give unsafe results, particularly with arches of high span/depth ratios. The failure criterion in these cases tends to be compressive failure of the barrel. This should, therefore, be checked in all cases where a mechanism approach is used.

20. Finally, it is our experience that, in most cases, the effectiveness of waterproof road surfacings is doubtful. We have on several occasions cored through abutments and arch barrels under waterproof road surfacings and been surprised at the pressure of water emanating from the hole. We can confirm that the use of plumb concrete near the springings is common, particularly in elliptical arches.

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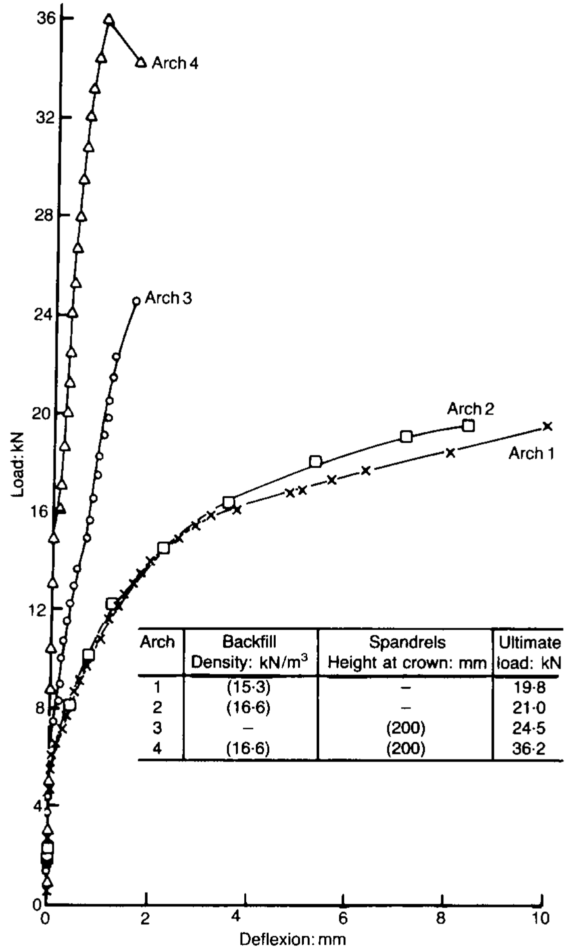
The Technical Note rightly emphasizes the important influence on the behaviour of masonry arches of the lateral restraint due to the backfill and spandrels. The Authors' proposals are confirmed and quantified by model tests that have been carried out at Bolton Institute of Higher Education.

22. Under the sponsorship of the Science and Engineering Research Council and the Transport and Road Research Laboratory, a number of model semicircular masonry arches have been tested. The work has been carried out as part of the wider programme of research currently being undertaken in Britain. The first series of arches tested at Bolton were built using half-scale bricks with the following dimensions: span 1000 mm, ring thickness 55 mm, and fill depth at crown 100 mm. Subsequent arches were built using full-scale bricks: span 1500 mm, ring thickness 100 mm, and fill depth at crown 150 mm. A typical test arch is shown in Fig. 5. Variables considered in the experimental investigations were: the influence of the backfill properties (density and angle of internal friction); load distribution; and spandrel wall stiffening on the behaviour of semicircular masonry arches. Loading was applied at quarter span in the first series and at third span in all subsequent tests.

23. All arches tested have failed as a result of the formation of a four hinge mechanism. The lateral restraint of the arch ring due to the backfill and spandrel walls was seen to influence the hinge positions nearest the springings, and to improve the ultimate load carrying capacity of the arch. The restraining of the arch on account of the backfill and spandrels is illustrated by comparing the load/deflexion responses of the arch ring (underneath the load point) for four test results (Fig. 6). The stiffening effect of the backfill and spandrels on the pre-failure

Fig. 5. Model arch



Arch	Backfill Density: kN/m^3	Spandrels Height at crown: mm	Ultimate load: kN
1	(15·3)	–	19·8
2	(16·6)	–	21·0
3	–	(200)	24·5
4	(16·6)	(200)	36·2

Fig. 6. Comparison of load/deflexion responses

behaviour is clearly shown by the reduction in the deflexion of the arch with backfill and spandrels (arch 4) compared to those arches without (arches 2 and 3). The influence of backfill and spandrels on the failure load is also apparent. The addition of backfill and spandrels to the arch ring increased the failure load of the arches by 43% and 83% respectively.

24. Throughout the loading history of each arch, a comprehensive series of backfill pressure measurements were recorded around the extrados of the ring. Initial results indicated a significant build-up of pressure on the side of the arch ring remote from the load when the arch was subjected to KEL loading at either quarter or third span. From the test results it was clear that the backfill provided a significant restraint to the deformation of the arch. The magnitude of the maximum pressures recorded, between 20–30 kN/m^2, was in excess of both the

active and at rest pressures. However, in all of arches tested, the pressures were also significantly less than the Rankine passive pressure.

25. While there is clearly an appreciation of the significance of the restraint due to the backfill and spandrels, a mathematical model suitable for a design analysis of masonry arches has yet to be developed.

Dr Harvey and Mr Smith

We are sorry to have given the impression that we claim novelty for the idea that horizontal fill pressure has an effect on an arch, when this was certainly cited in many papers before the end of the 19th century. Alexander and Thomson's book, *The scientific design of masonry arches*,[13] will serve as an example. We regret that we cannot cite a reference but believe that similar comments were made at the end of the 18th century. It is clear, however, that most twentieth century engineers ignored such effects in their analyses.

27. Our own work on arch analysis stems from difficulties with demonstrating the safety of a high-rise segmental bridge, using the work presented by Heyman in 1981[3]. This resulted in programs for pocket computers[9] and micros,[14] which were demonstrated in Edinburgh in 1984.[15]

28. We agree with the need for great care in assigning values to the properties of fill which cannot be physically investigated. We have been at some pains to stress the need to investigate the sensitivity of the analysis of a particular bridge to variations in such parameters.

29. We also agree that there is considerable difficulty in assessing the likely positions of the hinges in a mechanism analysis under complex loading cases. We have therefore stressed the need[9,14] for the engineer to receive graphical output showing a complete line of thrust. The effect of parameters which are not well defined should be carefully investigated by repeated analysis. Sensitivity analysis takes time, and will be carried out only if it can be done easily with fairly rapid response from the computer.

30. We certainly agree that anything short of mastic asphalt cannot be regarded as a waterproof road surfacing. The application of some of the modern bridge deck waterproofing systems to arches is likely to be particularly difficult. Rankine recommended that waterproofing should be applied to the back of the arch ring, using Puddle Clay.[16] One may wonder what would happen if a water main should burst within the fill.

References

12. Falconer R. E. and Jones K. S. The assessment of masonry arch bridges using commercial software. *Proc. Int. Conf. on Structural Faults and Repair*, London, 1987, **2**, 337–341.
13. Alexander and Thomson, *Scientific design of masonry arches*. Dublin Private Printing. University Press, Dublin, 1900.
14. Harvey W. J. and Smith F. W. The assessment and design of masonry arch structures using a microcomputer. *Proc. 2nd Int. Conf. on Civil and Structural Engineering Computing, London*, Dec. 1985.
15. Harvey W. J. Micro-computer aided analysis of masonry arch bridges. *Seminar on Masonry Arch Bridge Testing and Analysis.* Scottish Development Department, Glasgow, Nov., 1984.
16. Rankine W. McQ. *Civil engineering and applied mechanics*, 1862.